Volume II of II

FINAL
ARBOREAL STUDY REPORT

BLACKWELL FOREST PRESERVE LANDFILL SITE
DUPAGE COUNTY, ILLINOIS

Montgomery Watson File No.: 1252008

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Forest Preserve District of
DuPage County, Illinois

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Appendix D
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Front Cover: Schematic representation of the environment and C flows to, within, and out of the root system of a perennial fruit crop. Rectangles, valves and arrows represent rates, processes and flows, respectively. (See article by J. G. Buwalda on pages 131–140.)

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RESPONSE OF ROOTS TO MECHANICAL IMPEDANCE

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ATWELL B. J. *Response of roots to mechanical impedance.* ENVIRONMENTAL AND EXPERIMENTAL BOTANY **33**, 27–40, 1993.—The response of roots to mechanical impedance has been addressed in the literature largely from the physical point of view. The properties of soils which cause them to become impenetrable by roots have been analysed in detail, with particular reference to soil texture. Factors such as high soil cohesion (in clay soils) and high angle of internal friction (in sandy soils) contribute to soil strength. However, root growth often involves radial deformation of the soil near the growing apex, requiring a consideration of soil compression as well. While soils of all textures can impede root growth, those with high clay content are thought to be most inhibitory. Predictions of soil strength can also be obtained from penetrometer probes with different diameters and tip shapes. A precise physical analogue of root growth is not possible but probes which penetrate soil by deformation around the tip give surprisingly good estimates of *relative* soil strength. The capacity of roots to minimize friction with the soil and expand radially is thought to account for the lower absolute resistance perceived by roots than by penetrometer probes. Roots oppose strong soil by forces of osmotic origin acting on both the soil and the expanding cell walls. The response of roots is, however, poorly understood. Cortical cells tend to become broader and shorter, causing the root axis to thicken. Root volumes and osmotic pressures change as a result. The role of ethylene as a mediator of structural changes is in question. Root (and shoot) carbohydrate metabolism is also changed by impedance in a way that produces a favourable balance of biomass above and below ground and prevents carbohydrate deprivation to growing tissues. However, the co-ordination of changes in anatomy and metabolism remains a mystery. The scope for selection of plants tolerant to mechanical impedance is discussed and there are reasons for optimism if new screening criteria are adopted.

Key words: Compaction, ethylene, impedance, root, soil.

1. INTRODUCTION

THE response of roots to mechanical impedance has occupied agriculturalists, plant biologists and soil physicists for at least the past century. While our understanding of the complex physical changes in soils under compression grew throughout this time, an understanding of root response lay relatively dormant long after the elegant pioneering studies of PFEFFER.[56] In the 1950s and 1960s the groups of TAYLOR in the U.S.A. and BARLEY in Australia published a series of landmark papers on the physics of strong soils and how they are penetrated by roots and steel probes. This work laid the foundations for a flow of later papers which have refined our quantitative predications of root growth during impedance.[23] The physiology of roots growing in impeded conditions is, however, only vaguely understood. There are disparate and contradictory reports on the anatomy, hormone physiology and carbohydrate metabolism of these organs and a cohesive description of the biology still eludes us.

This review gives an overview of the soil factors which impose mechanical impedance on roots and how resistance is best measured. This aspect is covered very briefly and the reader is best referred to the excellent review by BARLEY and GREACEN.[15] Later reviews by GREACEN[35] and BENNIE[16] also give comprehensive accounts of root growth in strong soils. The response of roots to impedance is then discussed, with the hope that a biologist's view on the subject might give useful indications of fertile new ground for research. Finally, attempts to find genetic variation in plant response to strong soils are appraised.

2. THE MORPHOLOGICAL RESPONSE OF INDIVIDUAL ROOT AXES TO MECHANICAL IMPEDANCE

Optimal root growth requires an unconstrained pathway through the void space of the soil. The negative impact of soil compaction on root elongation is well documented[12,66] but there is considerable variation between individual reports on the degree of the growth response. Comparisons between experiments are generally inconclusive unless they take into account other factors such as the plant species (see Section 5), soil moisture, temperature and texture[16] and root diameter (see Section 3.3).

Figure 1 gives an impression of the inhibition of root growth in cases where soil strength has been estimated with a penetrometer probe (see Section 3.2). In all cases reported here and elsewhere in the literature, strong soils inhibit the extension of primary roots. However, there are few reported cases of soil compaction completely preventing root extension[20] and penetrometer resistances as high as 6 MPa did not prevent the continued, albeit slow, elongation of roots of peanuts (Fig. 2).

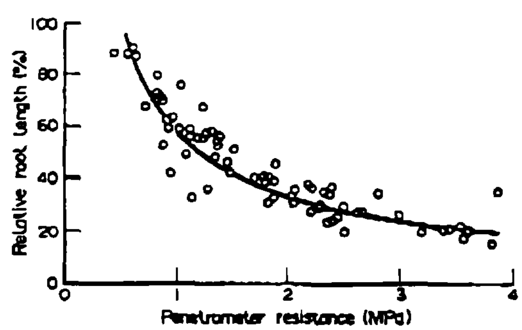

FIG. 1. Relationship between the relative root length of 70-day-old maize, cotton, wheat and groundnut plants and penetrometer pressure. Reprinted from BENNIE[16] (p. 403) by courtesy of Marcel Dekker, Inc.

The agreement between different experiments is very limited, but Fig. 1 shows that commonly encountered levels of mechanical impedance (> 2 MPa) are likely to reduce total root length and root elongation rate by at least 50%. These data help illustrate the potential impact of soil compaction on root development under field conditions. More studies in which soil conditions and plant species are varied methodically would help reveal the impact of individual factors on growth responses to mechanical resistance. For example, WARNAARS and EAVIS[71] looked at the effect of particle size on growth of roots through sand. In addition, an assessment of the genetic variation in root tolerance to compaction under a single soil regime has been reported.[47]

The response of root morphology to mechanical impedance is complex. The inevitable decrease in elongation of impeded roots is often accompanied by thickening (radial expansion) of

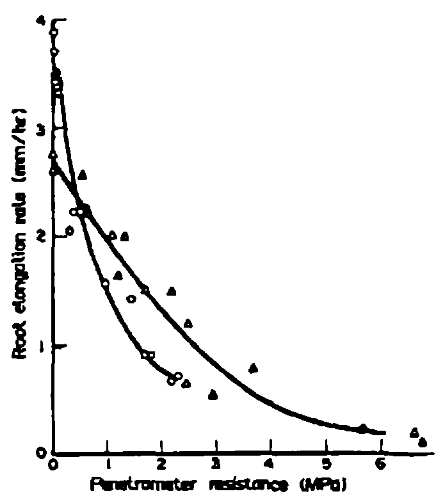

FIG. 2. Elongation rates of primary roots of cotton (○) and peanuts (△) growing for a period 40–80 h after transplanting in soils compacted to different degrees at a range of water contents (3.8–7.4% H_2O). Reproduced from TAYLOR and RATLIFF[67] (pp. 400–401) by courtesy of the American Society of Agronomy, Inc.

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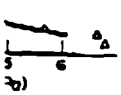

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the root axes.[4,13,24,47,60,76] The degree of thickening of the root, like the elongation rate, depends on the particular experimental conditions. For example, radial thickening in response to soil compaction varied from *ca* 15%[4,24] to 30–120%.[47] Specifically, roots of pea thickened in response to mechanical impedance by as little as 15% in EAVIS' study[24] but more than 100% in MATERECHERA *et al.*'s[47] experiment. The extreme inhibition of axial growth found by MATERECHERA *et al.* (93%) compared to that observed by EAVIS (60%) might go some way to explaining these dramatic differences in root thickening.

While expanding and mature root tissues are thicker in many cases where roots are constrained, the apex is relatively unaffected and tapers in a manner typical of unimpeded roots.[5,24,52] Finely tapered root apices might evade the resistance imposed by soil aggregates and penetrate soil pores more readily[22,35] (see Section 4.1). The potential for friction between such tapered apices and soil particles will be dealt with in Section 3.2.

Total root volume (and therefore mass) is not necessarily reduced by soil strength because the shorter root axes are often proportionately thicker.[8] In cases of more severe impedance, however, the volume of radicles is sharply reduced.[24]

3. STRONG SOILS AND THE FORCES WHICH ROOTS EXERT ON THEM

Root growth through a granular matrix such as soil involves the resolution of a number of forces. The physics of root growth (axial and radial stresses) must be considered alongside the compression and failure characteristics of the particular soil in order to generate a quantitative prediction of stresses on roots during mechanical impedance.[57] To further complicate matters, the frictional interaction between the root and soil must be considered, in spite of few data being available on the surface characteristics of the growing roots. Efforts to make a quantitative analysis of root growth pressures go back to PFEFFER's classical studies on *Vicia* and maize roots[56] and can be traced forward to the recent literature.[11–15,26,30,49] While the techniques for measuring the physical forces exerted by roots have changed little, the mathematical solution of the process has been developed to a point where fixed general relationships might now be applied through models.[25,35,57] Some elusive issues which remain are the biological response to mechanical impedance (i.e. the extent to which roots respond to soil strength) and the physical interaction between the root surface and the soil particles, particularly with respect to the lubricating action of root exudates.[20] These factors are probably largely responsible for the remaining discrepancies between estimates of mechanical impedance using probes and observed root growth rates.[16,50] For example, the possibility that roots can evade zones of compaction by sensing the existence and position of void spaces (trematotropism) has been addressed[22] but has not been resolved at this stage. There is a possibility that roots very close to soil pores in a hard soil can sense the position of the pore and grow towards it.[22] Artificial soils might not be an ideal system in which to identify this phenomenon, particularly while the chemistry of the putative signal molecule is unknown. Such a molecule is likely to be of biological and possibly microbial origin, and therefore might only be observed in undisturbed systems.

3.1. *The soil*

While high soil strength is the direct result of the physical state of the undisturbed soil, its existence is best defined as a *reaction* of the soil to forces exerted by the growing plant,[15] in this case, the root. This empirical and, for the soil scientist, more obscure definition leaves the alternatives of a bioassay for soil strength (penetrability of soil by roots) or the generally preferred option of steel probes which approximate the axial thrust of a plant root.

One widely observed characteristic of strong soils is the decrease in void space (increase in bulk density) which arises from the close packing of the soil particles.[3,15,43] While an increase in bulk density is not universal in strong soils,[2,5] it is likely that the physical compression of soils by heavy equipment leads to many of the field problems with high soil strength.[17,18,34,75]

Further compression of soils by roots is likely to occur, at least in localized zones (millimetre scale) adjacent to the growing apex;[15] this is most conveniently considered as a zone of plastic failure adjacent to the root surrounded by a zone of elastic failure.[37,51] When the packing density is low, or the void spaces between aggregates are large,[15,20] there is not likely to be a lot of re-orientation and compression of soil particles by the roots. The general (Coulomb) equation used to describe the shear failure of a soil undergoing little or no compression is:

$$s_n = c + \sigma_n \tan\phi \qquad (1)$$

where s_n is shear strength, c is cohesive strength, σ_n is the normal load and ϕ is the angle of internal friction. This equation cannot be applied to all soil–root interactions and often requires a measurement of compressibility as well as c and ϕ.[15] For example, values of ϕ greater than 35° (high internal friction as found in sands) are likely to confound the analysis of shear failure. In general, the high compression index (ease of compression) of clays suggests that they readily become impenetrable;[39] this is consistent with the relationship describing high clay soils as having a greater propensity to stop root growth[28] and penetration of probes.[16,20] However, sands with high internal friction can also present high shear strength and a mechanical barrier to root growth.[5,21] Generalizations on soil texture are not necessarily relevant to all soil–root combinations and might break down for particular plant species (with characteristic root shapes, rhizosphere chemistry, etc.) or mineralogical classes (e.g. hard-setting metal-hydrous oxide coated sands). The common approach to estimating soil strength is to drive a steel probe of some known dimension and tip shape into soil, thereby deriving a pressure, usually quoted as penetrometer pressure or point resistance (q_p).

3.2. *Do probes give a good estimate of the mechanical impedance perceived by roots?*

An analysis of the penetration of soils by probes has been discussed in detail elsewhere.[36,51] However, it should be said that the penetrometer probe, while only constituting a simulation of the growing root, often gives data which correlate well with the soil strength perceived by roots in a relatively homogeneous matrix.[16] For example, Eavis[24] and Greacen and Oh[37] found that pea root extension was inversely related to penetrometer resistance, while Bennie and Botha[17] and Atwell[5] found that field sites with high penetrometer resistances were also characterized by slow root extension in cereals. These effects can confidently be ascribed to mechanical impedance rather than poor aeration on the criteria defined by Eavis[25] and Warnaars and Eavis.[71] The potent interaction between soil compaction and aeration should be borne in mind when the response of roots is being analysed.[70]

Cockcroft *et al.*[20] showed experimentally that the point resistance (q_p), which is derived from the resistance to penetration and probe dimensions, is inversely related to radicle elongation. They also showed that a decreased voids ratio was associated with stronger soil and suppression of radicle elongation. In this case, a probe with a 60° tip angle gave an impressive correlation with root growth as the soil was increasingly compacted.

Special mention should be made of soils where the deviations between penetrometer readings and the resistances perceived by roots are likely to be most extreme. Aggregation is common in soils where the clay content exceeds 8–10%; the formation of aggregates is sought as desirable for the structure of agricultural soils. The formation of large, stable aggregates often leads to an increasing overestimate of the soil strength by penetrometer probes; the ratio between penetrometer pressure and root growth pressure rose from 1.8 to 3.8 over the range of increasing aggregate size used by Misra *et al.*[50] This implies that soil amelioration which leads to better root penetration and drainage properties might not be reflected in smaller penetrometer resistances. Roots can grow along the boundaries between peds, thereby avoiding the resistance to penetration of the bulk soil.[15,16]

Another source of variation between probes and roots is the existence of friction between the soil particles and penetrating shaft. This friction is a composite of frictional resistance to soil penetration by the tip and drag due to the curved exterior of the root (skin friction). The exact degree of friction between the root and soil cannot yet be measured directly. Ingenious attempts to quantify skin friction[15,20,64] give some estimates of the total frictional resistance to extension. A strong case is made that friction between steel

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probes and the soil far exceeds that between root and soil[20] and this explains much of the discrepancy between penetration of soil by blunt probes and roots.[36] This needs to be confirmed over a wide range of conditions and root morphologies.

It is conceivable that roots have evolved features which minimize the friction with soil. In particular, the zone of elongation in most roots is small (5–12 mm), meaning that skin friction is experienced over a short section of rapidly expanding tissue (see Section 3.3). A further compression of the zone of elongation in response to mechanical impedance[5,8] inevitably reduces the friction perceived by the root. Such roots show a proliferation of root hairs near the tip.[3,24] These hairs help anchor the non-growing portion of the root while the diminished zone of elongation finds a path through the soil.[64] The shorter zone of elongation and diminished root meristem in mechanically impeded roots[11] might allow roots to react more sensitively and grow into the available soil pores.[16,22,71] Finally, increased exudation of lubricating mucigels in response to mechanical impedance would reduce further the impact of skin friction. A number of biological approaches to the issue of soil–root friction are possible. Root mutants, particularly those with altered apex shape or root hair density, might be a useful tool to vary the magnitude of soil–root friction without changing other root properties. Characterizing the viscous properties of mucigels and the suppression of synthesis of mucilagenous agents (e.g. waxes and extracellular glycoproteins) by molecular techniques would help to address the impact of soil–root friction from a biological point of view.

Even if soils are finely structured and soil–root friction is small, blunt probes have been shown to deform soil in a manner different from roots.[20] Penetrometer probes commonly have a 60° angle (30° semi-angle) at the tip of the shaft, with the result that they deform the soil 'spherically', characterized by a re-orientation of particles near the tip of the probe.[20] On the other hand, root apices are more tapered and root axes thicken in response to mechanical impedance (see Section 4.1), with the result that the radial stresses predominate as roots penetrate the soil. Roots therefore cause a 'cylindrical' failure of the soil followed by axial extension into the zone of weakness formed in front of the root cap. This model has received wide acceptance over the past 25 years.[1,20] Probes with finely tapered tips deform soil 'cylindrically' like a root, but such probes bring new problems because of the increasing amount of probe–soil friction as the tip becomes more acute.[36] Tapered probes (e.g. 10°) can nevertheless give more satisfactory estimates of soil strength than blunt probes.[70]

The lower pressures required for 'cylindrical' than for 'spherical' penetration of soil[1] are especially significant in cases where the internal friction (ϕ) is large (sandy soils) and the root apex encounters high friction.[15] It has not been demonstrated directly that the lower pressures required for cylindrical compression of the soil translate to a saving in metabolic (osmotic) energy by the root. Again, root morphology mutants which have constitutively different axis diameters and root tip morphologies might reveal differences in extension rate per unit of osmotic pressure (axial extensibility). The smaller load opposing axial root extension which results from 'cylindrical' compression of the soil might, however, be achieved only through greater root diameters, which would dilute the incoming osmotic solutes. This would in turn annul some of the energy savings of a 'cylindrical' pattern of soil deformation by requiring increased rates of solute import (see Section 4.3).

The easier penetration of soils by roots than probes is widely acknowledged. EAVIS[24] estimated the stress required to drive a probe into compacted soil was four to eight times that required for the root to penetrate the soil, in spite of the dimensions of both being similar. STOLZY and BARLEY[64] showed a much smaller difference, but their data still confirm that roots penetrate soils easier than probes. Much of the variation between probe and root resistance is thought to be due to clay content of soil.[16] This discrepancy in resistances is reflected in the observations that roots elongate in soils with penetrometer resistances of 3.0 MPa,[66] while the root turgor (or osmotic) pressure driving growth is less than 1.5 MPa.[8,11]

3.3. *The exertion of pressure by roots*

Root cells grow by exerting turgor pressure on the visco-elastic cell walls in the zone of elongation. This pressure is normally opposed by the wall pressure, generated presumably as the bonds within the walls develop tension. However, in compacted soil, the solid matrix adjacent to the roots adds an additional pressure to the wall pressure which opposes turgor pressure. This additional pressure diminishes the effective turgor pressure and suppresses cell expansion. These variables can be described by the equation:

$$P = -(W + \sigma) \qquad (2)$$

where P = turgor pressure, W = wall pressure and σ = the pressure imposed by the soil matrix on the root.[37] The implication of this equation is that W, like P, has a single value for any individual cell. In fact, W is different for the longitudinal and radial walls of an elongating cell and hence the expression of P is different in the axial and radial directions of root growth. The importance of distinguishing between axial and radial growth pressure was recognized by PFEFFER[56] who made accurate estimates of growth pressures in *Vicia* and maize roots. The pressures PFEFFER calculated, by measuring forces and root cross-sectional areas, were in the range 0.7–2.5 MPa axially and 0.4–0.6 MPa radially,[30] whereas the estimates by MISRA *et al.*[49] suggest that radial pressure in three species exceeded axial pressure. The reason for this discrepancy might be the plant species tested, although this is unlikely. MISRA *et al.* used cylinders of chalk to estimate the radial pressure exerted by roots as opposed to PFEFFER's plaster of Paris blocks. The diffusion of gases through the constraining materials might not have been the same, leading to differences in the flux of ethylene from the root and modified rates of lateral swelling (see Section 4.2). This would influence the estimates of radial growth pressure.

Whether the radial pressures are greater or less than the axial pressures in impeded roots, the key issue is that radial pressures are exerted over a large area compared to the point impact of the axial forces. For example, BARLEY and GREACEN[15] calculated that the radial and axial pressures reported by PFEFFER[56] in *Vicia* roots exert 5 and 0.3 kg wt of force in the respective directions along a 4 cm length of root. A significant radial force might not be exerted over the entire 4 cm section of root, considering that the thickening of roots is often localized near the apex[5] and expanding tissues (less than 1 cm long) are likely to be the main source of plastic compression. However, even moderate radial pressures are doubtless of great significance in causing soil deformation adjacent to the zone of elongation and relief of resistance to axial growth. The corollary was confirmed by ABDALLA *et al.*[1] who showed that the resistance to radial expansion by roots was at least 50% less than resistance to axial extension.

4. HOW ROOTS RESPOND TO MECHANICAL IMPEDANCE

The physiological changes which occur in roots (and emerging shoots) during and after exposure to mechanical impedance are less thoroughly documented than the physics of root–soil interactions.[16] Some reasons for this were expressed by BARLEY[14] and they remain largely valid. BARLEY[13] reported some of the anatomical changes in roots, realizing that the forces required for growth depend on the root dimensions as much as turgor pressure of the apical tissues. The responses of individual cell types to mechanical pressure and the consequences for root metabolism are still poorly understood. Better information on aspects of metabolism such as exudation, assimilate use, ion transport, plant growth regulators and cell wall rheology will give insights into both the physics of root growth in compacted soils and the consequences of restricted root growth on whole plant performance.

4.1. *Anatomy*

A recurring conclusion from experiments on mechanically constrained roots is that the diameter of the impeded root axes increases compared with unimpeded controls.[5,11,24,52,60,62,76] BARLEY[13] showed that the application of pressure to developing 1 cm root apices was necessary to elicit the commonly observed changes in root dimensions. Tissues appear unable to thicken in response to mechanical impedance once primary growth has ceased. This increase in the diameter of impeded roots (and compressed emerging shoots)[60] is generally accompanied by a decrease in elongation. There is no evidence that the two responses can be uncoupled in an impeded system, suggesting that there is a unique signal

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leading to the production of short, thick roots. Alternatively, the radial swelling of roots might be a secondary response to reduced longitudinal growth through a re-orientation of cell wall microfibrils to a more vertical pitch.[69] The mechanisms leading to this gross morphological change are only likely to be elucidated through a union of hormone physiology, cell wall ultrastructural studies and water relations. Recently developed *Arabidopsis* mutants which have naturally radially thickened roots might be useful in these experiments.

The general view that roots thicken in response to mechanical impedance depends on the dimensions of the soil–root system. While major root axes (e.g. seminal roots) thicken in a compressible matrix where pores are too small for root penetration, there is a large number of finer lateral roots capable of penetrating soil pores of 0.1–0.5 mm diameter. GOSS[32] manipulated the size of glass ballotini to show that primary laterals of barley were able to enter relatively fine pores (160 μm diameter). This observation underlies a paradox in root response to mechanical impedance. Roots which are too thick to find a tortuous path between packed soil particles are likely to find an easier passage through the soil by expanding radially and filling the soil axially. However, those roots fine enough to penetrate the soil pores will not improve their passage through the soil by thickening and might indeed hinder it. The suitability of wheat to 'non-tilled soil'[73] might owe more to this phenomenon than the pressures generated by root apices. Anatomical studies on the capacity of lateral root tissues to alter cell shape in response to impedance are called for.

In major root axes where the root cortex thickens in response to mechanical impedance, the stele is often unresponsive.[4,5,61,62] The main evidence to the contrary comes from WILSON *et al.*[76] who showed that barley roots grown in ballotini had altered cortical and stelar dimensions, with the diameter of the stele being greater in the terminal 4 cm of the impeded roots. These data are based on distance from the apex, however, and therefore do not consider effects of tissue age. BENNIE[16] also quotes a case of altered stelar dimensions in three crop species during impedance of the roots; together with the data of WILSON *et al.*[76] this suggests a need for further investigation. SCHOLEFIELD and HALL[61] ingeniously grew ryegrass roots through rigid pores of known dimensions and found that the ability to penetrate pores depended on the size of the root cap and stele rather than the diameter of the entire root. Whether the size of the root tip dictates the pore size through which roots grow,[74] or the stele, is not certain. However, the experiment does show that roots can grow through rigid pores without an increase in diameter of the stele. It is interesting to note that mature cereal roots in the field slough off the cortex in response to ageing[40] or drought (unpublished data). One role of the cortex in immature root tissues might be to generate radial pressures and thereby create a pathway for root growth. The cortex would, from this point of view, become superfluous after root maturation.

The radial thickening of cortical cells is therefore probably a targeted response, leading to the yielding of the radial and tangential cell walls. The increase in cortical thickness is at least in part the result of greater cell diameters.[4,13,24,76] However, this increase in cortical cell diameters is often compensated for by shortening of the long axis of cells, resulting in an unchanged[13] or slightly reduced[5] cortical cell volume in impeded roots. The inverse relationship between cell length and breadth is illustrated in the data of EAVIS,[24] although cell dimensions were not determined directly and unconfirmed assumptions were made about cell file numbers.

There is more information on the shape of differentiated cells than the rate of production of new cells by impeded roots. The physics of root growth suggests that the cells of the root meristem might be relatively protected from mechanical pressure, therefore implying that cell division responds less to mechanical impedance than cell expansion. There is some evidence to support this view. SCHUURMAN *et al.*[62] claim that the number of cells was not reduced by impedance while cell length was reduced. It is not clear whether both the number of cell files and total cell numbers were equally insensitive to impedance. EAVIS[24] showed a modest drop in the number of vacuolated cells in response to soil strength but no significant change in the number of non-vacuolated (meristematic?) cells. The latter might simply suggest that there were more inactive, non-vacuolated cells in the impeded roots. The indirect methods of estimating cell dimensions[24] limit the interpretation of the data. From the values given, it can be shown that an impedance of *ca* 34 g wt resulted in a reduction of *ca* 40% in both number and length of vacuolated cells. This implies a potent effect of mechanical impedance on cell production and elongation. However, the abrupt confrontation of the pea root with a mechanical resistance and the short duration of the treatment (24 hr) compared with the cell cycle of at least 12 hr[68] calls for a similar test over a long period of steady-state impedance. In the studies of Barley[15] and Atwell[5] the reduction in root elongation rate was approximately matched by the reduction in longitudinal cell length, suggesting that there was little effect of mechanical impedance on the number of transverse cell divisions. The evidence for an increase in the number of cortical cell files[13,76] in mechanically impeded roots suggests that any decrease in the flux of cells into individual files might be compensated for by a small increase in the number of cell files. In roots of lupin, however, there was no increase in cortical cell file number.[4] It is proposed that the meristem and process of cell proliferation are more affected by signal transduction in the root (from the zone of elongation perhaps) than by a direct effect of physical pressure. The lag in recovery from mechanical impedance[33] indicates that the meristem is suppressed for days after impedance, either through changes within the apex or signal transduction from other tissues. Much more work is needed to put this issue on solid ground.

4.2. *Plant growth regulators*

After some years of speculation that ethylene mediates the swelling of mechanically impeded roots. Kays *et al.*[41] reported that *Vicia* roots evolved ethylene at about six times the control rate when they grew against a mechanical barrier. They cautiously suggested that ethylene was a growth factor in mechanically impeded roots, causing radial thickening of the root axes. This view was reinforced by the observation that restricted epicotyls of pea also thickened and evolved ethylene at an increased rate.[31] This led to continuing speculation that ethylene, and possibly auxin,[33] were responsible for the gross morphological changes seen in impeded plant roots. The issue remained in abeyance until the late 1980s when Whalen,[72] Moss *et al.*[52] and Sarquis *et al.*[60] published on the role of ethylene in regulating the morphology of mechanically impeded roots. Whalen[72] grew roots against a barrier, imposing a brief period of axial resistance on them. Why the rates of ethylene evolution did not rise transiently in response to this, as it did in Kays *et al.*'s[41] experiment, is not clear. It would need to be established that the oxygen status of the chambers was adequate before the ethylene evolution could be ascribed directly to mechanical impedance. Accumulation of the ethylene precursor, ACC, is reminiscent of a block in its conversion to ethylene by anoxia. Furthermore, the rise in ethylene production brought about at the moment of contact with the barrier might have been transient for each individual root axis and difficult to quantify.

Moss *et al.*[52] used inhibitors of ethylene action and synthesis to manipulate endogenous ethylene produced during mechanical impedance. They found that maize responded to the packed matrix of ballotini by growing shorter, thicker roots and evolving ethylene faster. Similar root morphology could be induced by supplying exogenous ethylene. However, the addition of 2,5-norbornadiene, a volatile inhibitor of ethylene action, reversed the effect of *exogenous* ethylene by making roots longer and thinner but did not affect the dimensions of mechanically impeded roots. The same unexpected result was observed when aminoethoxyvinylglycine (AVG) was added to inhibit ethylene synthesis. These data, together with the boost in endogenous ethylene production *after* the onset of root morphological changes, suggest that ethylene was not the causal factor in root thickening. Sarquis *et al.*[60] found a very different result. Ethylene evolution increased rapidly with the onset of mechanical impedance imposed on maize seedlings in a triaxial cell. The removal of impedance caused a decrease in ethylene evolution. This showed that endogenous ethylene could be produced in a sufficiently responsive manner to trigger the morphological responses to impedance. A range of inhibitors of ethylene action and synthesis were tested to find a combination which was successful in reversing the morphological effects of mechanical impedance on roots and coleoptiles (decreased elon-

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gation and radial expansion). It is unclear why these data diverge so strikingly from those of Moss *et al.*[52] The modest success of AVG and silver thiosulphate in reversing the morphological effects of mechanical impedance,[60] while 2,5-norbornadiene and AVG alone failed to do so,[52] can best be ascribed to the characteristics of the different inhibitors. Rates of penetration of inhibitors are always a potential problem and the particular success of AVG and silver thiosulphate combined suggest that they were able to block the effects of ethylene before any cytological changes were set in train. The longer term nature of the experiment by Moss *et al.*[52] might have allowed other plant growth regulators, such as auxin, to begin to exert an effect. Auxin has been considered as an agent in altering the morphology of mechanically impeded roots,[42] either through a direct effect or via a secondary stimulation of ethylene synthesis.[34] If ethylene were to be ruled out as an agent in root thickening, it would have to be confirmed that both wound ethylene and auxin-induced ethylene are susceptible to interference by 2,5-norbornadiene and AVG.

The levels of plant growth regulators have not been thoroughly measured in mechanically impeded roots. LACHNO *et al.*[42] and Moss *et al.*[52] found that abscisic acid did not increase in mechanically impeded roots of maize. ATWELL and HENSON (unpublished data) found a decrease of 40–70% in the abscisic acid level of 5 mm lupin root apices after a long period of mechanical impedance. This weakens the case for abscisic acid as an agent in the response of roots to mechanical impedance, although low concentrations of abscisic acid might be expected in slow-growing roots.[59]

4.3. *Assimilate import and utilization*

The metabolism of impeded roots is a subject which deserves more attention but is, to date, largely unexplored. There are two principal reasons for investigating this issue. Firstly, the generation of osmotic (therefore turgor) pressure for growth against strong soil relies on the deposition of high concentrations of solutes, a large proportion being small organic molecules such as sugars.[4] While the magnitude of the wall pressure, and hence the rheological properties of the cell walls, are no doubt important determinants of root growth pressure, it is also critical for the elongating tissue to import osmotic solutes continuously as a source of turgor pressure.[37]

Secondly, the use of assimilates by roots in compacted soil is relevant to the overall carbon economy of the plant because roots are a major sink for assimilates early in crop development.[38,45] If large amounts of assimilates are required for roots to penetrate strong soils, there is potential for a commensurate down-regulation of shoot growth.

The only reports of the assimilate levels in freely growing vs restricted roots show that the carbohydrate levels increased in response to increasing impedance. Although BARBER and GUNN[9] did not tightly pack the ballotini through which their roots grew, the carbohydrate levels were at least 20% greater in the entire root system. The differences might have been greater near the apices. ATWELL[5] took wheat roots from field sites which had been loosened mechanically or remained compacted. The soluble sugar concentrations were always higher in tissues of the same age when elongation was mechanically impeded. The reverse was true for soluble amino acids. MASLE *et al.*[45] also grew seedlings of wheat in compacted and loose soil, showing large increases in soluble sugar concentrations in roots which were mechanically impeded. Therefore, sugars accumulate generally in response to soil compaction and thereby contribute to turgor pressure.[37] The cost of this increase in soluble sugars appears to be less rapid expansion rates,[45] providing the conditions for solute build-up. There is a strong case to look at assimilate import into root growing zones in relation to growth, in a similar way to that in droughted roots.[63] The characteristic swelling of impeded roots would provide an interesting comparison with the thinner roots produced during water deficits.

The metabolism and growth of roots which are mechanically impeded are greatly perturbed. This is supported by ^{14}C transport and carbon budgets on wheat seedlings in the field.[7] One day after labelled carbon was applied to the shoots, the label was concentrated in the terminal 1 cm of the unimpeded seminal roots, while slower growing impeded roots had label more evenly distributed throughout the terminal 5 cm. Furthermore, the total amount of label reaching the apices of unimpeded roots was three-fold greater than in roots from compact soil.[7] The rapid growth of unimpeded seminal roots (1.78 vs 0.60 cm/day) was presumably responsible for the rapid assimilate import by the growing cells. Respiration rates were also elevated in these fast-growing 1 cm apices.[7] However, when the growth rates of root axes were taken into account, a unit length increase in impeded roots required about twice as much carbon as the same extension of an unimpeded axis.[7] This estimate is necessarily approximate but serves to illustrate the perturbation in carbon metabolism which mechanical impedance brings about. There appears to be a reduced sink strength (demand for assimilates) in impeded roots[15] rather than an increased allocation of assimilates into osmotic pools.[7] One could speculate that the major response of roots to mechanical impedance is a radial swelling brought about by differential loosening of cell walls, rather than a large re-direction of assimilates into osmotic pools by active transport. It might be that solute import into growing apices cannot be further derepressed in response to mechanical impedance and therefore osmotic adjustment is only achieved by a decrease in growth rate.[4,8,37] Studies of local solute deposition will help resolve this as it did in the case of droughted maize roots, where solute build-up was shown to be partly due to changes in tissue expansion rates.[63]

The amount of carbon exuded by roots growing in compacted soils has been the subject of much speculation but the issue remains largely uncontaminated by facts. While carbon exudation increases in some cases (e.g. cereals in sterile ballotini beads)[9] and not others (wheat roots in packed soil),[7] there are difficulties in establishing the phenomenon in the field, where it is of most ecological and agricultural interest. The establishment of mycorrhizal associations and competition with developing shoots for carbon are two such issues of interest. The technical problems arise principally from an inability to separate the metabolism of exudates by rhizosphere microflora from carbohydrate metabolism in the root; respired carbon can be derived from either source. Sterile systems help overcome this issue[10] but might still be confounded by spurious estimates of root respiration.[53] No data are available on the influence of soil strength on rhizosphere microbiology, or how the microflora, in turn, influence root growth and function under these conditions.

The carbon metabolism of shoots of plants with mechanically impeded roots has received little direct attention; some of the possible causes for decreased shoot growth are outlined by Masle and Passioura,[46] among them the deprivation of carbohydrates to the developing leaves as roots compete for assimilates. Indeed, the greater root : shoot ratio sometimes reported in mechanically impeded wheat seedlings is consistent with this notion.[44] However, it appears that young seedlings have a complex series of responses to strong soils such as reduced transpiration and increased photosynthetic capacity.[44] The result is that sufficient assimilates reach the roots[4,6] and shoots[6,46] of plants growing in strong soil, thereby establishing a new shoot–root equilibrium appropriate to the diminished function of the roots. Masle *et al.*[45] showed that both shoot and root tissues of wheat seedlings grown in compacted soil were richer in carbohydrates than tissues from loose soil. This relationship was independent of the ambient CO_2 level and photosynthetic rate. This indicates that the rate of growth was controlled by factors other than assimilation rate. A modulation of shoot growth in response to diminished root growth has also been identified when rooting volume was restricted while water and nutrient levels were high.[58] Under normal field conditions, there is an increased allocation of carbon to shoots as the cereal plant matures.[38] It is not clear in the case of mechanical impedance whether this shift in resource allocation to shoots can be sustained by the compromised root system. An increasing likelihood of drought is one possible consequence of the ontogenetic shift in carbon allocation, particularly if total transpiration continues to increase over time. However, the responsiveness of shoot growth[32,46] and water-use efficiency[44] to mechanical impedance imposed on seedlings suggests that the physiology and development of the whole plant might be well adapted to strong soils.[18] This needs to be tested in longer term experiments.

5. GENETIC VARIATION IN THE RESPONSE TO MECHANICAL IMPEDANCE

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dimensions. This was extended to a number of classical studies on the ability of roots, particularly of cotton and peanuts, to penetrate hard soil[66] (*cf.* Fig. 2). There were marked differences between these two species in the root elongation rate and root growth pressures generated.[67] However the capacity of roots to grow through strong soils relative to loose soils might vary more with differences in the number of root axes (monocots vs dicots) than intrinsic properties of individual axes.[16]

While it is appreciated that root dimensions, especially radial thickening, play a major role in determining the pressure exerted by roots in a densely packed matrix, this has not been widely exploited in interspecific comparisons. A recent survey of eight monocot and 14 dicot species by MATERECHERA *et al.*[47] showed a great deal of interspecific variation in root diameters with an impressive correlation between the ability to elongate in hard soil and root thickness. Furthermore, the tendency of roots to swell in response to mechanical impedance also correlated with capacity to elongate in strong soils. This illustrates the power of simple measurements like root diameter in understanding mechanisms and providing manageable selection criteria, in this case for ability to penetrate strong soils. Similar screening experiments in solutions of high osmotic pressure might even lead us to useful species rankings for tolerance to soil strength.[48]

A survey of the osmotic pressure of root apices along these lines would be salutary and with modern osmometers, relatively simple. Early studies[11] show that the difference between species might be in the order of 0.2–0.3 MPa which is a readily detectable difference. This approach gives only one variable in the growth analysis. The threshold pressure at which cell walls begin to yield to turgor pressure[37] remains a major unknown in the growth equation. Threshold turgor pressure can only be determined in a more comprehensive experiment in which P and σ [see Equation (2)] have been measured over a wide range of soil strengths.[37] This is beyond the scope of a simple screening, but might be of interest in cases where theory predicts differences in both wall yielding properties and turgor pressure. For simplicity, the values of osmotic pressure might be easier to interpret if measured in unimpeded roots because increases in osmotic pressure by mechanical impedance would not be confounded by differential rates of volume expansion in various genotypes (see ATWELL).[4] Screening simply for osmotic pressure under optimal conditions (reflecting import of solutes) is more likely to give heritable differences in tolerance to mechanical impedance.

Shoot growth and yield components are also susceptible to the effects of soil compaction. A genetic analysis would be most profitable by comparing cultivars, as has been attempted for dry beans (*Phaseolus vulgaris* L.).[29] However, it is still not known how much intraspecific genetic variation exists for *root* characters which determine tolerance to mechanical impedance (root diameter, root hair formation?). Variations in shoot response to mechanical impedance are more likely to be the consequence of selection pressure on root characters than a reflection of direct selection pressure on genes coding for shoot characters. Indeed, the effects of no-tillage on shoot development in wheat are probably a consequence of cultivar differences expressed early in seedling development.[19] These differences were established during the period of rapid root growth. Therefore, in spite of the difficulty of extracting roots from soil, the screening of seedling root characters should logically precede detailed genetic studies on the shoots.

6. CONCLUDING REMARKS

Root growth through strong soils is necessarily inaccessible; this has led to a paucity of direct observations and a great deal of experimentation in artificial soil systems and ballotini. This approach has been vindicated because we are now quite confident that roots penetrate hard soils by a combination of cylindrical stress and axial extension. This mechanism is founded in impeccable physics and contrasts with the axial resistance estimated from blunt, steel probes. The energy saving embodied in this mechanism of root growth is further improved by low root–soil friction and compression of the growth zone during impedance. Roots have evolved to be sophisticated biological probes. However, in spite of the subtlety of root behaviour in hard soils, penetrometer probes give generally good estimates of soil strength.

Root metabolism is radically altered by impedance; cortical cells swell radially, ethylene is synthesized and osmotic solutes accumulate in the root apices. The anatomical changes have been tentatively linked to ethylene release and might be considered adaptive because they mitigate the effects of axial resistance on growth. Other changes are still being evaluated; for example, the growth physiology is still hampered by a lack of knowledge of cell wall properties and import of osmotic solutes (solute deposition rates). Equally, the role of plant growth regulators is not well described and is currently at a stalemate where the pre-eminent molecule, ethylene, is concerned. It is little wonder that we know so little about the pattern of shoot development imposed by impeded root systems. Understanding the signalling process is another challenge for the burgeoning science of root–shoot communication.[55]

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DRYING, CRACKING, AND SUBSIDENCE OF A CLAY SOIL IN A LYSIMETER

J. J. B. BRONSWIJK[1]

The relation between changes in water content and swelling and shrinkage processes was studied by exposing an undisturbed heavy clay soil in a lysimeter to evaporation at controlled conditions in the laboratory during a period of 82 days. Changes in water content were measured with tensiometers and by weighing the lysimeter. Swelling and shrinkage were determined by measuring the surface subsidence. The loss of water from the clay soil amounted to 45 mm, 40% less than the loss of water from a comparable silty soil lysimeter. Drying of the clay soil was restricted to the top 15 cm of the soil. As much as 67% of the water loss originated from the top 7.5 cm of the soil. Simultaneous shrinkage in the clay soil resulted in a three-dimensional decrease in volume of 34 mm, consisting of a crack volume of 22 mm and a surface subsidence of 12 mm. The clay soil exhibited the successive occurrence of structural shrinkage, isotropic normal shrinkage, isotropic residual shrinkage, and isotropic normal shrinkage again. The occurrence of normal and residual shrinkage could be predicted by the water content changes in the soil and the shrinkage characteristics of soil aggregates. Water loss in the structural shrinkage phase occurred from interaggregate pores and could therefore only be qualified from the lysimeter experiment.

Due to the presence of clay minerals, the volume of soil aggregates in clay soils changes as water content changes. In dry periods, the volumes of individual aggregegates decrease, which in the field becomes visible as shrinkage cracks and surface subsidence. In wet periods, swelling causes crack closure and upward movement of the soil surface. The physical behavior of clay soils and their potential for agricultural production are determined by this alternating swelling and shrinkage.

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When cracks are closed, infiltration of water into the soil is very slow, and ponding and surface runoff are likely to occur. In such a situation, crop growth may be hampered by O_2 deficiency, and pasture may be destroyed by cattle hoofs. With respect to environmental consequences, the application of liquid manure in such periods may lead to rapid transport of pollutants to surface waters by runoff.

After a dry period the soil will be cracked, resulting in high potential infiltration rates and storage capacities. Capillary rise from the water table and evapotranspiration may then be hampered by low hydraulic conductivities. Resulting water shortage is enhanced by bypass flow: part of the precipitation flows through shrinkage cracks to subsoil layers, thus bypassing the relatively dry root zone. This process again has some important environmental effects. Pollutants may rapidly reach the water table or, when pipe drainage has been installed, travel through these drains to surface waters again.

Understanding and predicting transport processes in swelling clay soils require knowledge of the dynamic process of soil cracking and surface subsidence. Therefore, the relation between drying and shrinkage is of great importance.

Haines (1923) and Keen (1931) defined three shrinkage phases:

> Normal shrinkage: the decrease in volume of clay aggregates is equal to the loss of water; the aggregates remain fully saturated; Residual shrinkage: upon drying the volume of the aggregates still decreases, but the loss of water is greater than the decrease in volume; air enters the pores of the aggregates; Zero shrinkage: the soil particles have reached their densest configuration; upon further water extraction, the volume of aggregates remains constant; the loss of water is equal to the increase in air volume in the aggregates.

In the field, sometimes a fourth shrinkage phase, preceding the three mentioned above, can be distinguished: structural shrinkage (Stirk 1954). Structural shrinkage occurs in very wet

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soils. When such soils dry, either by evaporation or drainage, large water-filled pores may be emptied. As a result, aggregates can get a somewhat denser packing. On the whole, the changes in volume in this shrinkage phase are negligible, but the loss of water can be considerable.

Studies on the relation between water content and swelling and shrinkage have been carried out on aggregates (e.g., Grossman et al. 1968, Franzmeier and Ross 1968, Reeve & Hall 1978, Reeve et al. 1980, and Bronswijk and Evers-Vermeer 1990), small cores (e.g., Perroux et al. 1974, Berndt and Coughlan 1977, and Yule and Ritchie 1980a), large cores (Yule and Ritchie 1980b), and in the field (Aitchison and Holmes 1953, Jamison and Thompson 1967, Yaalon and Kalmar 1972, Yaalon and Kalmar 1984, Hallaire 1984, and Bronswijk, in preparation).[2] Different problems inhibit the analysis of the relation between changes in water content and changes in volume. Studies on aggregates and small cores generally do not yield the magnitude of water loss in the structural shrinkage phase because structural shrinkage is strongly dependent on soil structure, and therefore large samples are required. Furthermore, the load of upper soil layers may influence the geometry of swelling and shrinkage in the field, and this effect is not taken into account when dealing with aggregates or small cores taken out of the field into the laboratory. In large cores and field situations, on the other hand, changes in volume are difficult to determine. Moreover, measuring water contents is difficult. Of the latter two, large cores have the advantage that they resemble a field situation and that the water balance can be determined rather accurately in a well-controlled laboratory environment.

The objective of this research was to predict the shrinkage of a clay soil from water content changes in the soil and easily measured physical properties of soil aggregates. Because of the advantages mentioned above, a lysimeter experiment was conducted. The undisturbed heavy clay soil inside the lysimeter was subjected to evaporation in the laboratory during a period of 82 days. During drying of the soil, the various terms of the water balance were determined together with surface subsidence and crack volumes. In order to explain the observed phenomena in the clay soil in the lysimeter, water retention curves and shrinkage characteristics were determined using soil aggregates.

[2] J. J. B. Bronswijk, 1991, The relation between vertical soil movements and water content changes in swelling clay soils, submitted to Soil Sci. Soc. Am. J.

METHODS AND MATERIALS

Soil type

The investigated Bruchem heavy clay soil originates from the river district in the central part of the Netherlands. The soil is classified as a typic Fluvaquent, very fine clayey, mixed, illitic-montmorillonitic mesic (Soil Survey Staff 1975). Its clay content ranges from 52 to 69%. The soil was in use as pasture.

Soil aggregates

In the early spring of 1985, when the soil was saturated, seven natural aggregates of about 25 cm^3 were taken from each 20-cm layer of the soil at the sampling site. To ensure their complete saturation, the aggregates were placed on a saturated sand bed for another 2 weeks. From the seven aggregates per soil layer, three aggregates were used to determine water retention curves on a sand box and with pressure membrane apparatus. One aggregate was used to determine the density of the solid phase. The remaining three aggregates were used to determine shrinkage characteristics by immersing the aggregates briefly in Saran F310 Resin (resin to solvent ratio 1:5 by weight). The applied Saran coating is impermeable to water but permeable to water vapor (Brasher et al. 1966). The coated aggregates were dried in the laboratory. When the aggregates dry, the elastic coating remains tightly fitted around the aggregates. By weighing and water displacement, both volumes and weights of the aggregates were determined at different stages of drying. After about 3 weeks, weight losses became negligible, and the resin-coated aggregates were dried in the oven at 103°C in order to measure their final dry volumes and dry weights. Void ratios (i.e., volume at pores divided by volume of solids) and moisture ratios (i.e., volume of water divided by volume of solids) were calculated, using the measured values of density of solid phase.

Lysimeter

One large undisturbed soil core was sampled in the field in early spring when the soil was saturated. The height of the empty PVC core was 70 cm and the diameter 27.6 cm. The top 20 cm of the soil had been removed to eliminate the possible influence of grass roots on soil shrinkage. With a hydraulic pump and a cutting edge, the empty core was carefully pushed 60 cm into the soil, and dug out. Subsidence of the soil surface in the column during sampling was negligible. Thus, the upper 10 cm of the core remained empty, and the lower 60 cm was filled with undisturbed soil from a depth of 20 to 80 cm.

In the laboratory, the core was placed on a sand base containing a drainage system, allowing water to flow into and out of the bottom of the lysimeter (Fig. 1). By using a Mariotte bottle set-up, the ground water level was kept constant at 55 cm below the soil surface during the experiment. The soil surface was kept bare. In the present experimental set-up, the water balance of the clay soil over a certain time interval reads: $\Delta W = E - B$, in which ΔW is the decrease in water storage in the soil (mm, decrease is positive), B is the cumulative flow of water through the bottom of the lysimeter (mm, positive upwards), and E is the cumulative actual evaporation (mm, positive). Variable B was measured by weighing the Mariotte bottle. The value ΔW was determined by weighing the whole lysimeter, and E was calculated from the difference of B and ΔW. Ceramic cup tensiometers were installed at 3, 12, 22, 32, and 42 cm below the soil surface. The tensiometers were inserted through oval-shaped holes (2-cm height) in the lysimeter wall. Thus, tensiometers could freely move downward as the soil shrank. Tensiometers were recorded automatically, using a five-way valve, a pressure transducer, and a recorder. The average surface subsidence of the soil in the lysimeter was measured using nine thin needles that were lowered every other day onto the soil surface at varying, randomly selected positions.

After 36 days of drying, the decrease in water storage in the soil became negligible. The potential evaporation demand was then increased using ventilators. The experiment was stopped after the tensiometer at a depth of 12 cm had exceeded its air-entry value. At that time, the experiment had lasted 82 days.

An estimation of crack volume in the lysimeter was made at the start and the end of the experiment as follows. At the time of taking the soil core in the field, four samples in rings of 30-cm diameter × 5-cm height were taken at five depths in the surroundings of the sampling site of the lysimeter. Aggregate bulk density, derived from the shrinkage characteristics, was compared with ring-sample bulk density. Interaggregate porosity could thus be calculated. After concluding the lysimeter experiment, the interaggregate porosity was determined inside the lysimeter itself, again by comparing aggregate bulk density with soil bulk density.

Final gravimetric water contents in the lysimeter were determined, as well as distribution of the weight of the solid phase in the column.

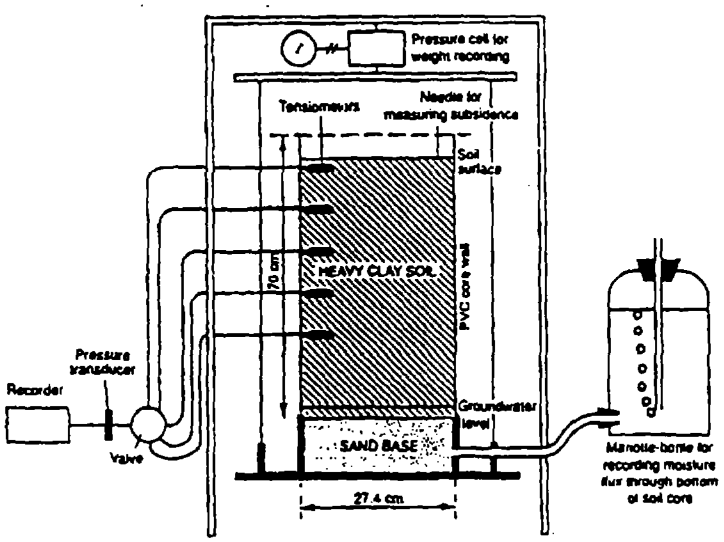

FIG. 1. Setup of the experiment.

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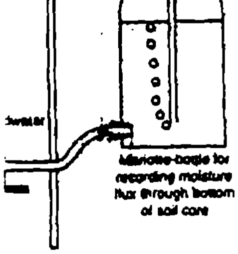

During the experiment, a similar experiment was conducted with an artificially packed soil column in order to compare the water balances of the two soil types. This "Blokzijl silt" consists of 85% silt, 3% clay, and 12% sand.

Data processing

Tensiometers at 3, 12, 22, 32, and 42 cm below soil surface were considered to represent the soil layers of 0–7.5 (layer 1), 7.5–17 (layer 2), 17–27 (layer 3), 27–37 (layer 4), and 37–50 (layer 5) cm deep, respectively. The measured pressure heads in the lysimeter were converted into gravimetric water contents using the water retention curve determined on aggregates. Because the weight of the solid phase of each layer was determined, the total water storage in each layer could be calculated. Due to rapid drying of the topsoil, the tensiometer at 3-cm depth passed its air-entry value rather quickly, i.e., after 9 days. From then on, the water contents of layer 1 were calculated by subtracting the calculated cumulative changes in water storage of layers 2 to 5 from the measured change in water storage of the whole lysimeter (column weights).

Bronswijk (1990) concluded that shrinkage at natural loads occurring in Bruchem heavy clay soil was isotropic. Therefore, the measured one-dimensional soil surface subsidence of the soil was converted into a three-dimensional decrease in soil matrix volume and into crack volume by using the following equations (Bronswijk 1989):

$$\Delta V = \left\{1 - \left(1 - \frac{\Delta z}{z}\right)^3\right\} V \qquad (1)$$

$$V_{cr} = \Delta V - z^2 \cdot \Delta z \qquad (2)$$

with

- V = volume (m^3) of soil matrix at saturation,
- z = layer thickness (m) of soil matrix at saturation,
- ΔV, Δz = decrease in volume of soil matrix (m^3) and layer thickness (m), respectively, as a result of shrinkage (both positive), and
- V_{cr} = change in crack volume (m^3).

The calculated change in crack volume of the soil, computed with Eq. (2), was compared with the measured value obtained with the core sampling method outlined before.

RESULTS AND DISCUSSION

Aggregates

The shrinkage characteristic of the soil aggregates is shown in Fig. 2A. The measured shrinkage characteristic shows the three classical shrinkage phases: normal shrinkage from ν = 1.15 to 0.5, residual shrinkage from ν = 0.5 to 0.18, and zero shrinkage from ν = 0.18 to 0. The water retention curve is pictured in Fig. 2B. As is common in heavy clay soils, the water retention curve shows a very steep decrease in pressure head with decreasing water content. The greater and most important part of the shrinkage process in the considered soil can be regarded as normal shrinkage. The whole pressure head range in which water uptake by plant roots

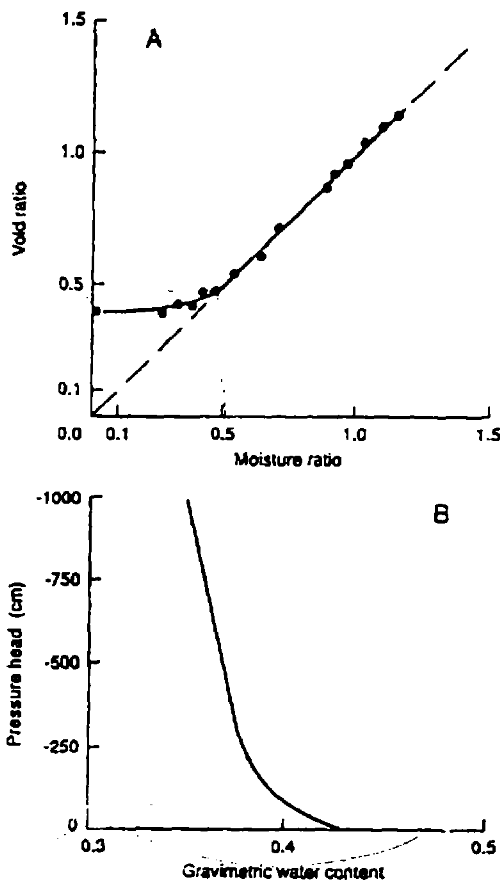

FIG. 2. Physical properties of the clay soil used in the experiment: A, shrinkage characteristic of soil aggregates; and B, water retention curve.

takes place lies within the normal shrinkage phase.

Lysimeter

The water balance of the clay soil is depicted in Fig. 3A. During the first 10 days of the experiment, the initially high evaporation rate decreased gradually until a more or less constant rate of 0.76 mm/day was reached. From day 36 on, when the potential evaporation demand was increased by ventilators, the evaporation rate was equal to about 0.83 mm/day. The upward flow through the bottom of the clay-soil lysimeter quickly became constant at a rate of about 0.37 mm/day. The water storage in the clay soil decreased rapidly during the first 15 days. Thereafter, the evaporation became equal to the upward flow through the bottom of the lysimeter, so the water storage did not decrease anymore. After the potential evaporation demand had been increased at day 36, the evaporation rate increased, the upward flow of water through the bottom remained unaltered, and therefore the water storage in the soil decreased again. No equilibrium situation was attained again before the experiment was concluded. The cumulative evaporation of the Bruchem heavy clay soil was

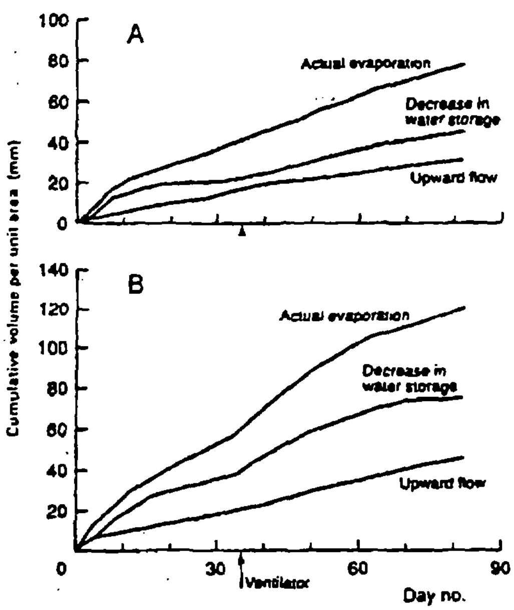

FIG. 3. Measured water balances of a lysimeter: A, with Bruchem heavy clay, and B, with Blokzijl silt. The potential evaporation was the same for both lysimeters.

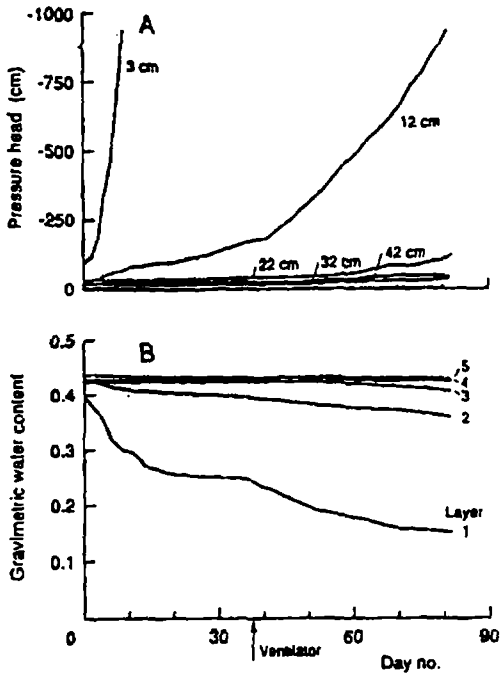

FIG. 4. Drying of Bruchem heavy clay at various depths: A, measured pressure head values (cm), and B, water contents. The water contents of layers 2–5 were derived from measured pressure head values and the water retention curve. The water content of layer 1 was calculated from the difference of the column weight and the water contents of layers 2–5.

about 65%, the cumulative upward flow about 73%, and the decrease in water storage 58% of the values of Blokzijl silt (Fig. 3).

The measured pressure head values in the clay soil showed a rapid decrease for the top tensiometer at 3-cm depth (Fig. 4A). The air-entry value of this tensiometer was already reached at day 9, due to the steepness of the water retention curve (Fig. 2B). The second tensiometer at 12-cm depth showed a gradual decrease in pressure head over the whole measuring period of 28 days. This indicates that, while the column weight implicated a steady state around day 30, the soil around the second tensiometer was still drying out, and therefore water inside the core was still redistributing. The tensiometers at depths of 22, 32, and 42 cm showed only very little drying. The water contents of the various layers of the clay soil are pictured in Figure 4B. The course of the gravimetric water content of layer 1 (0–7.5 cm) clearly reflected the two different evaporation regimes. The water content of this layer

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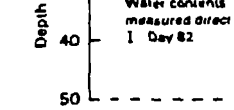

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reached a constant value of about 0.25 around day 22. When the potential evaporation demand was increased, the water content rapidly decreased, down to 0.15 at the end of the experiment. Only after about 50 days did the three lower soil layers begin to lose water. In Fig. 5, water content profiles at various times during the experiment are compared. At the end of the experiment, a very steep water content profile had developed with extreme water content gradients in the upper 10 cm of the soil profile. From Fig. 5 it follows that the directly measured gravimetric water content at the end of the experiment agreed well with the water content profile derived from pressure head values. This supported the method of using tensiometers and a water retention curve to derive gravimetric water contents for the clay soil in the lysimeter. The loss of water in the Bruchem heavy clay soil occurred mainly in the upper 15 cm of the soil, with 67% of the water loss originating from the upper 7.5 cm of the soil. The large gradients in the water content profile reflect the formation of a dry surface soil with low hydraulic conductivities on top of a relatively wet subsoil.

Due to the drying process described above, the clay soil cracked, and the surface subsided. The first 4 days, the measured surface subsidence in the clay-soil lysimeter was practically zero (Fig. 6). Thereafter, surface subsidence started. The subsidence rate was large in the beginning of

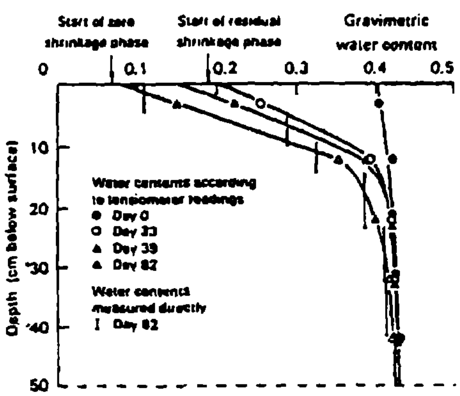

FIG. 5. Gravimetric water content profiles at various times during drying of Bruchem heavy clay soil. After conclusion of the experiment, the water content of the soil in the lysimeter was determined. These directly measured values are presented in the figure as well. Finally, the water contents where residual shrinkage and zero start according to the shrinkage characteristic (Fig. 2A) are indicated with a ↓.

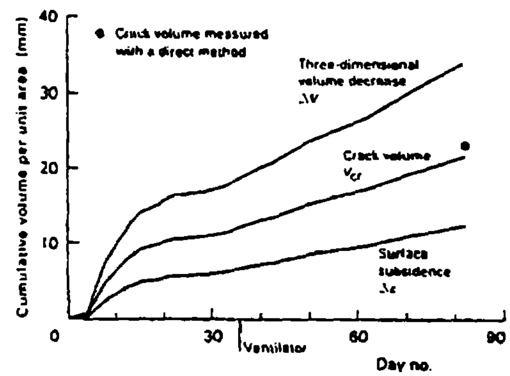

FIG. 6. Shrinkage of Bruchem heavy clay in a lysimeter upon drying. Surface subsidence was directly measured. Three-dimensional volume decrease and crack volume were derived according to Eqs. (1) and (2). A measured value of crack volume at the end of the experiment is indicated as well.

the experiment and became almost zero around day 25. After increasing the potential evaporation demand (day 36), the surface subsidence rate increased again. Cumulative subsidence amounted to 12.4 mm. Crack volume (expressed per unit area) increased by 21.7 mm, and three-dimensional shrinkage of the soil matrix equalled 34.1 mm. The directly measured change in crack volume at the conclusion of the experiment agreed well with the values derived from surface subsidence measurements.

In Fig. 7, the three-dimensional change in volume of the clay soil matrix, ΔV, is compared with the measured change in water storage, ΔW. The first 4 days, water storage in the soil decreased rapidly, while shrinkage of the soil was still very small. From day 4 to day 35 the decrease in water storage was about equal to the shrinkage rate of the soil. After the higher potential evaporation demand had been established at day 36, the decrease in water storage was again higher than shrinkage until day 70.

Around that time, the decrease in water storage in the soil equalled the shrinkage rate once again. This apparently strange behavior can be explained by looking at the drying front in the soil and at the shrinkage characteristic of the soil aggregates, as will be discussed in the next section.

Comparison between behavior of soil aggregates and soil in lysimeter

According to the shrinkage characteristics of the soil aggregates, we would expect normal

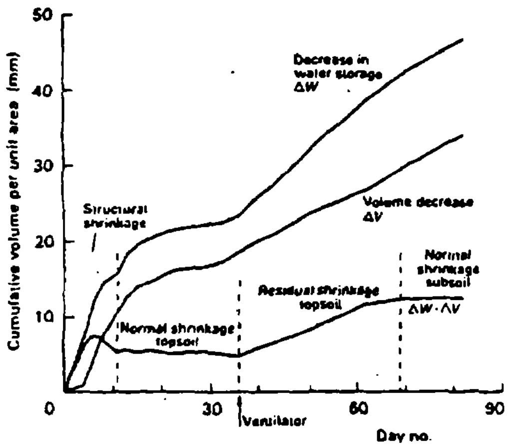

FIG. 7. Comparison between decrease in water storage ΔW and decrease in volume of the soil matrix ΔV of Bruchem heavy clay. For each period, the dominant shrinkage phase is indicated.

shrinkage to be the main shrinkage type in this soil. For normal shrinkage, the decrease in soil matrix volume has to be equal to the decrease in water storage, which is obviously not the case (Fig. 7). The loss of water without corresponding shrinkage during the first 4 days of the experiment, amounting to about 7 mm, has to be explained by the occurrence of structural shrinkage. In the present soil, water loss in the structural shrinkage phase originates from interaggregate pores, because a structural shrinkage phase is absent in the shrinkage characteristic of the soil aggregates (Fig. 2A). From day 4 to day 35, the shrinkage rate was more or less equal to the decrease in water storage, reflecting normal isotropic shrinkage of the soil matrix. The differences observed between the two are likely the result of an experimental error caused by the third-power dependence of calculated three-dimensional shrinkage on measured subsidence (Eq. (1)).

After the enhanced evaporation regime had been established at day 36, the decrease in water storage again became higher than the three-dimensional shrinkage rate. From the shrinkage characteristic of the soil aggregates (Fig. 2A) it can be concluded that residual shrinkage in this clay soil occurs below a moisture ratio of 0.50, which corresponds with a gravimetric water content of 0.19. From the water content profiles of Fig. 5, it appears that before day 30, at every depth in the soil profile, the water content was higher than this threshold value, so residual shrinkage did not take place. After day 36, however, the water content of the top layer was decreasing strongly because of the higher evaporative demand. At that time, the threshold value of 0.19 was reached in the top of the soil profile, and residual shrinkage started. The zero-shrinkage range, starting below moisture ratios of 0.18 (which equals a gravimetric water content of 0.07) was not reached in the clay-soil lysimeter.

The successive occurrence of structural shrinkage, normal shrinkage, and residual shrinkage during drying of the soil before day 70 is in agreement with other experiments on drying and shrinkage of clay soils (e.g., Yule and Ritchie 1980). Around day 70, however, residual shrinkage is succeeded by normal shrinkage again. The reason for this second occurrence of a normal shrinkage phase is probably that the water loss rate in the top layer, which is in the residual shrinkage phase, decreases around day 70, while the water loss rate in the subsoil, still in the normal shrinkage phase, became more prominent (Fig. 4B) at that time. As a result, the soil as a whole exhibits normal shrinkage again. It is possible that the enhanced water loss from the subsoil occurred by evaporation through the shrinkage cracks, but this could not be assessed in the present experiment.

CONCLUSIONS

The water storage in a heavy clay soil in a lysimeter decreased by 45 mm in 82 days due to evaporation. This drying process was accompanied by a shrinkage of the soil matrix of 34 mm, consisting of a crack volume of 22 mm and a surface subsidence of 12 mm.

The shrinkage behavior of the clay soil revealed the occurrence of structural shrinkage, isotropic normal shrinkage, and isotropic residual shrinkage. Structural shrinkage can only be derived from experiments on large undisturbed samples. The other two shrinkage phases can be predicted accurately using measured shrinkage characteristics of natural soil aggregates. After the successive occurrence of structural, normal, and residual shrinkage during prolonged drying, a second normal shrinkage phase occurred. This phenomenon was due to the fact that water loss from the subsoil, which was still in the normal shrinkage phase, became greater than water loss

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The loss of water in the clay-soil lysimeter amounted to 58% of the loss in a silty soil, at equal potential-evaporation rates.

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a forest and above cleared ground. Here Stevenson asserts that forests, regarded as radiating surfaces, react as do other radiating surfaces but that not enough reliable data are available for showing their quantitative effects.

Throughout his exposition Stevenson relies upon the well-chosen word. He uses no graphs, but still manages to express himself fairly lucidly when dealing with cumbersome data. His approach is critical and rational.

An historical note on the article itself is of interest here. While originally published in the *Proceedings of the Royal Society*, two limited printings were made in pamphlet form (*3*). Some years after Stevenson's death specimens of the pamphlet were found which, upon examination by experts, were adjudged forgeries. One of the proofs of forgery was the use of paper containing rag, esparto, and chemical wood. The presence of the latter indicates that the paper could not have been manufactured prior to 1874, a year after the actual publication date of the original pamphlets (*1*).

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Soil Depth Affects Windfirmness of Longleaf Pine

Longleaf pines (*Pinus palustris*) on the Escambia Experimental Forest in south Alabama seem most susceptible to windthrow where underlain by clay at a shallow depth. This was indicated by a survey of trees felled by hurricane Flossy in late September 1956.

Nine inches of rain fell within 48 hours just prior to and during the hurricane. Over the 2,500 acres where the survey was made the storm blew down about 300 trees ranging in size from saplings to large sawtimber.

After the storm, 57 soil borings were taken to determine conditions where windthrow had occurred. Down trees were segregated into three classes on the basis of depth to clay or sandy clay layers of the soils on which they had been growing. Proportion of windthrown trees on each class of soil was computed and compared with the proportion of Experimental Forest area in that class. Results are shown in Table 1.

The tabulation indicates very clearly that more trees shallowly underlain by a clay or sandy clay layer were windthrown than would be expected from the proportion of area falling into that class. Restricted root development on shallow soils, along with greater saturation of such soils (due to slowdown of rainwater percolation through the less permeable clay layer) are believed to be primarily responsible. Surface soils on the experimental forest are generally sandy, particularly in the A horizon, and infiltration is usually rapid until a heavy soil is reached.

These results suggest that, following windstorms, foresters managing longleaf pine on the Gulf-coast might well start scouting for windthrow on soils with clay or sandy clay within two feet of the surface.

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TABLE 1.—PROPORTION OF WINDTHROWN TREES BY CLASS OF SOIL

Depth to clay or sandy clay	Forest area in soil class	Wind-thrown trees in soil class
(*Inches*)	(*Percent*)	(*Percent*)
24 or less	46	90
25 to 48	29	7
More than 48	25	3
Total	100	100

FIG. 1.—Clay or sandy clay within two feet of the surface tends to reduce windfirmness of longleaf pines.

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Mechanics of root growth

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Key words Elongation Extensibility Mechanical stress Osmoregulation Soil strength Water stress

Summary A model is developed for the rate of elongation of a root tip in terms of the balance of pressures acting on the root. Differentials of this equation give expressions for the changes in root elongation rate with respect to soil water potential and soil mechanical resistance. The model predicts that root cells osmoregulate against both water stress and soil mechanical resistance with similar efficiencies which are less than 100%. Analysis of published data leads to the conclusion that root tips of pea osmoregulate with 70% efficiency. A working equation is developed for the elongation rate of roots in conditions of combined water stress and mechanical resistance.

Model

Plant roots are assemblages of cells acting in concert. Elongation of a root and the response of the root to its environment reflect cell elongation and the response of cells to their environment. Cells are in mechanical equilibrium such that their internal and external mechanical stresses balance. An equation can be developed for the mechanical equilibrium of cells which incorporates the cell-wall extensibility factor as developed in plant physiology[10,11]. Differentials of this equation give the sensitivities of cell and root elongation rate to changes in the terms in the equation of equilibrium. Combination of experimental results from a number of authors leads to the conclusion that root elongation rate decreases linearly with increasing mechanical stress acting externally on the root. External mechanical stress can arise from the resistance to root elongation arising from soil strength. This study provides a link between basic physiological studies and the observed behaviour of roots in the field.

Plant cells are in equilibrium such that the total internal water potential, Ψ_i, is balanced by the total external potentials which comprise the external water potential, Ψ_o, plus any additional mechanical stresses or pressures, M:

$$|\Psi_i| = |\Psi_o| + M. \qquad (1)$$

Here, and in what follows, compressive pressures are considered to be positive and tensile pressures are considered to be negative. The soil water potential is composed of osmotic, π_o, and matric, Ψ_m, components:

$$\Psi_o = \pi_o + \Psi_m. \qquad (2)$$

Within the plant cells, with their semi-permeable membrane walls, the negative osmotic potential which is produced by dissolved ionic and molecular species gives rise to an osmotic pressure $\Pi_i = -\pi_i = |\Psi_i|$. In parts of this paper, water potentials, Ψ, will be considered in terms of the moduli of their values, $|\Psi|$. This overcomes problems with sign changes.

The additional mechanical stresses are composed of a wall pressure component, W, resulting from tension in the cell walls, and a component, σ, resulting from external pressures exerted on the cells from the surrounding medium. Thus,

$$M = W + \sigma. \qquad (3)$$

In the case of the cells of elongating plant roots, σ is the pressure that the root has to exert to deform the surrounding soil. From (1), (2) and (3):

$$|\Psi_i| = |\Psi_o| + W + \sigma. \qquad (4)$$

The rate of cell elongation, R, is related to the tension in the cell walls and hence to the wall pressure component, W, by

$$R = m(W - W_c), \qquad \text{for } W > W_c, \qquad (5)$$

where W_c is a critical wall pressure component which has to be exceeded for elongation to occur, and m is an extensibility factor[9,10,11]. A combination of Equations (4) and (5) gives the elongation rate

$$R = m[|\Psi_i| - |\Psi_o| - W_c - \sigma]. \qquad (6)$$

Equation (6) can be used to investigate the extensibility factor, m, and the effects of soil strength and water stress on the rate of elongation of roots. To do this, it will be assumed that the equation, which was derived from considerations of single cells, can also be applied to the elongation zone of plant roots. It must be realised that the terms on the right-hand-side of Equation (6) are not all independent. In particular, Ψ_i, changes in response to changes in the other terms. This process is known as osmotic adjustment or osmoregulation. It is one form of plant compensation in response to external stresses.

Greacen and Oh[9], using the seminal roots of pea (*Pisum sativum*) determined the critical wall pressure as

$$W_c = 0.34\,\text{MPa},$$

and the extensibility factor at 20

$$m = 81 \pm 8\,\text{mm}$$

They also investigated osmoregu
sidered in terms of derivatives
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external water potential, Ψ_o, on t
(*Arachis hypogaea* L. cv. Virginia
of cotton (*Gossypium hirsutum* L.
Differentiation of Equation (6) w
to zero gives

$$\frac{\partial R}{\partial|\Psi_o|} = m\left[\frac{\partial|\Psi_i|}{\partial|\Psi_o|} - \right.$$

This shows that for the roots of
water potentials,

$$\delta\Psi_i = \delta\Psi_o.$$

Greacen and Oh[9] also conclude
potential was matched by a corre
tial:

$$\frac{\partial|\Psi_i|}{\partial|\Psi_o|} = 1.03 \pm 0.0$$

which supports Equation (1)
eson[13] indicate a finite value of

$$\frac{\partial R}{\partial|\Psi_o|} = -18.4\,\text{mm}$$

for the roots of maize (*Zea mays*
later.

The dependence of root elong
can also be examined by differ

$$\frac{\partial R}{\partial\sigma} = m\left[\frac{\partial|\Psi_i|}{\partial\sigma} - \right.$$

It is reasonable to assume that
to be zero as a first approxima
pea[9] show that

$$W_c = 0.34\,\text{MPa}, \tag{7}$$

and the extensibility factor at 20°C as

$$m = 81 \pm 8\,\text{mm day}^{-1}\,\text{MPa}^{-1}. \tag{8}$$

They also investigated osmoregulation by pea roots which is best considered in terms of derivatives of Equation (6). They considered the results of Taylor and Ratliff[18] which showed that there was no effect of external water potential, Ψ_o, on the rate of elongation of roots of peanut (*Arachis hypogaea* L. cv. Virginia Bunch) down to $\Psi_o = -0.7$ MPa and of cotton (*Gossypium hirsutum* L. cv. Empire) down to $\Psi_o = -1.2$ MPa. Differentiation of Equation (6) with respect to Ψ_o and setting the result to zero gives

$$\frac{\partial R}{\partial|\Psi_o|} = m\left[\frac{\partial|\Psi_i|}{\partial|\Psi_o|} - 1\right] = 0. \tag{9}$$

This shows that for the roots of these species down to these particular water potentials,

$$\delta\Psi_i = \delta\Psi_o. \tag{10}$$

Greacen and Oh[9] also concluded that a change of external soil water potential was matched by a corresponding change in cell osmotic potential:

$$\frac{\partial|\Psi_i|}{\partial|\Psi_o|} = 1.03 \pm 0.06, \tag{11}$$

ich supports Equation (1). However, the results of Mirreh and Ketch-eson[13] indicate a finite value of

$$\frac{\partial R}{\partial|\Psi_o|} = -18.4\,\text{mm day}^{-1}\,\text{MPa}^{-1} \tag{12}$$

for the roots of maize (*Zea mays* L. cv. United 106), as will be discussed later.

The dependence of root elongation rate on soil mechanical resistance can also be examined by differentiating Equation (6):

$$\frac{\partial R}{\partial \sigma} = m\left[\frac{\partial|\Psi_i|}{\partial \sigma} - \frac{\partial|\Psi_o|}{\partial \sigma} - \frac{\partial W_c}{\partial \sigma} - 1\right] \tag{13}$$

It is reasonable to assume that $\partial\Psi_o/\partial\sigma = 0$, and $\partial W_c/\partial\sigma$ can be assumed to be zero as a first approximation. Experimental results for the roots of pea[9] show that

$$\frac{\partial|\Psi_i|}{\partial\sigma} = 0.7 \pm 0.04, \tag{14}$$

which is a measure of the efficiency of osmoregulation against soil mechanical resistance. This leaves

$$\frac{\partial R}{\partial\sigma} = -0.3\,\mathrm{m} \text{ for pea, or}$$

$$= -\mathrm{K}\,\mathrm{m} \tag{15}$$

in the general case. Note that if the efficiency of osmoregulation was 100%, then K would be zero, and soil mechanical resistance would have no effect on root elongation rate. In practice, it is observed that $\partial R/\partial\sigma$ is not zero, and so the efficiency of osmoregulation must be less than 100%.

The mechanical stress, σ, exerted by a root tip against soil resistance cannot be measured at the same time as elongation rate, R. R has been measured as a function of soil strength, Q_p, measured with penetrometer probes[7,13,18]. Penetrometers used in laboratory studies are usually conical with a 30° semi-angle, steel, and of 1–3 mm diameter. The results show that R decreases from its maximum value of R_{max} in an exponential-like manner with increasing soil strength, Q_p. This may be written

$$\frac{R}{R_{max}} = e^{-0.6931(Q_p/Q_{1/2})}, \tag{16}$$

where $Q_{1/2}$ is the value of penetrometer resistance that reduces relative root elongation rate, R/R_{max}, to one-half, and the exponent-0.6931 is $\log_e 0.5$ and results from the use of $Q_{1/2}$ in Equation (16). Some values of R_{max} and $Q_{1/2}$ are given in Table 1.

Additionally, information is available which compares growth pressure, σ, and penetrometer resistance, Q_p, for the penetration of root tips and probes into the surfaces of blocks of soil[4,12,20]. Here, growth pressure is defined as the stress, acting normally to the root surface, which a root has to exert to deform the soil around it. Growth pressure, σ, is expected to be numerically equal to $(|\Psi_i| - |\Psi_o| - W)$ as given by Equation (4). The results show that Q_p is always larger than σ, and that the ratio between them increases progressively with increasing soil strength being around 3 in "weak" soil (*e.g.* $Q_p = 0.5$ MPa), around 8 or 10 in "strong" soil (*e.g.* $Q_p = 5$ MPa), and perhaps even higher in yet stronger soil. The difference between σ and Q_p results from the different modes of soil deformation induced by roots and penetrometers[1,2,8]. The curve relating σ and Q_p must pass through the origin ($\sigma = Q_p = 0$) in extremely weak soil, and σ can never exceed the maximum growth pressures which roots

can exert, σ_{max}. Again, the l
type equation of the form

$$\frac{\sigma}{\sigma_{max}} = 1 -$$

where α has a value aroun
Equation (17) may be a
Ketcheson[13]. If it is a
$\alpha = 0.5\,\mathrm{MPa}^{-1}$, then estin
roots may be obtained. The
as:

$$R = 26.0 - 2$$

$$R = 19.1 - 1$$

$$R = 16.6 - 2$$

and

$$R = 12.5 - 1$$

In Equations (18), the coeff
average,

$$\frac{\partial R}{\partial\sigma} = -20\,\mathrm{mn}$$

This constancy suppor
The first term in Equa
decreasing soil water potent
within experimental error
$$R = 26 + 18.$$
where Ψ_o and σ are in MP
of $\partial R/|\partial\Psi_o|$ which was qu
For maize, the efficiency
not been estimated. All w
$\mathrm{Km} = 20\,\mathrm{mm\,day^{-1}\,MPa}$
for maize, then the exten
$$m = 61\,\mathrm{mm}$$
If the results in Equation
then it is also found tha

can exert, σ_{max}. Again, the limited available data suggest an exponential-type equation of the form

$$\frac{\sigma}{\sigma_{max}} = 1 - e^{-\alpha Q_p}, \tag{17}$$

where α has a value around $0.5\,\mathrm{MPa}^{-1}$.

Equation (17) may be applied to the tabulated data of Mirreh and Ketcheson[13]. If it is assumed that $\sigma_{max} = 1.3\,\mathrm{MPa}$ and that $\alpha = 0.5\,\mathrm{MPa}^{-1}$, then estimates of the pressures, σ, experienced by the roots may be obtained. Their results for four values of Ψ_o may be written as:

$$\left.\begin{array}{lll} R = 26.0 - 21.5\sigma,\ \mathrm{mm\,day^{-1}} & \text{for } \Psi_o = & -0.1\,\mathrm{MPa}, \\ R = 19.1 - 19.0\sigma,\ \mathrm{mm\,day^{-1}} & \text{for } \Psi_o = & -0.3\,\mathrm{MPa}, \\ R = 16.6 - 21.3\sigma,\ \mathrm{mm\,day^{-1}} & \text{for } \Psi_o = & -0.45\,\mathrm{MPa}, \\ \text{and} & & \\ R = 12.5 - 18.1\sigma,\ \mathrm{mm\,day^{-1}} & \text{for } \Psi_o = & -0.8\,\mathrm{MPa}, \end{array}\right\} \tag{18}$$

In Equations (18), the coefficient of σ seems to be fairly constant, and on average,

$$\frac{\partial R}{\partial \sigma} = -20\,\mathrm{mm\,day^{-1}\,MPa^{-1}}. \tag{19}$$

constancy supports the concept of a constant value of m.

he first term in Equations (18) decreases approximately linearly with decreasing soil water potential, Ψ_o, and Equations (18) can be written to within experimental error as

$$R = 26 + 18.4\Psi_o - 20.0\sigma,\ \mathrm{mm\,day^{-1}}, \tag{20}$$

where Ψ_o and σ are in MPa. From Equation (20) is obtained the value of $\partial R/|\partial \Psi_o|$ which was quoted in Equation (12).

For maize, the efficiency of osmoregulation ($E = (1\text{-}K) \times 100\%$) has not been estimated. All we know, from Equations (15) and (19) is that $Km = 20\,\mathrm{mm\,day^{-1}\,MPa^{-1}}$. However, if it is assumed that K is also 0.3 for maize, then the extensibility factor for maize is

$$m = 61\,\mathrm{mm\,day^{-1}\,MPa^{-1}}. \tag{21}$$

If the results in Equations (12) and (21) are substituted into Equation (9), then it is also found that

$$\frac{\partial|\Psi_i|}{\partial|\Psi_o|} = 1 + \frac{1}{m}\frac{\partial R}{\partial|\Psi_o|} = 0.7 \tag{22}$$

is obtained for the efficiency of osmoregulation of maize roots against water stress.

The results for pea roots of Greacen and Oh[9], who measured σ directly, can also be written as in Equations (18). In this case,

$$\left.\begin{aligned} R &= 25.3 - 70.6\sigma,\ \text{mm day}^{-1} \quad \text{for } \Psi_o = -0.285\,\text{MPa},\\ R &= 17.8 - 27.1\sigma,\ \text{mm day}^{-1} \quad \text{for } \Psi_o = -0.42\,\text{MPa},\\ &\text{and}\\ R &= 13.1 - 24.2\sigma,\ \text{mm day}^{-1} \quad \text{for } \Psi_o = -0.73\,\text{MPa}. \end{aligned}\right\} \tag{23}$$

It should be noted that their data at $\Psi_o = -0.285$ MPa were rather scattered. These data are consistent with

$$R = 30 + 25.3\Psi_o - 27\sigma,\ \text{mm day}^{-1}, \tag{24}$$

which shows that

$$\frac{\partial R}{\partial \sigma} = -27\,\text{mm day}^{-1}\,\text{MPa}^{-1}. \tag{25}$$

This consistent with Equation (15) and the value of $m = 81$ mm day^{-1} MPa^{-1} quoted by those authors. Again, it is found that if these values are substituted into Equation (9), then

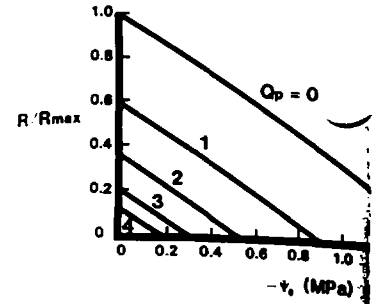
$$\frac{\partial|\Psi_i|}{\partial|\Psi_o|} = 0.7. \tag{26}$$

It therefore appears that the roots of pea osmoregulate against soil water potential and soil mechanical resistance with an efficiency of 70%. This is in contrast with the conclusions of Greacen and Oh[9] who obtained the result in Equation (11) on the basis of their data for $\sigma \sim 0.15$ MPa alone.

Equations (20) and (24) are remarkably similar, and it is possible to consider an average plant for which

$$\frac{R}{R_{max}} = 1 + 0.78\Psi_o - 0.85\sigma. \tag{27}$$

It can be seen from Equation (27) that, in the absence of mechanical stress ($\sigma = 0$), root growth is predicted to cease at $\Psi_o = -1/0.78 = -1.28$ MPa. This would correspond to wilting. Similarly, in the absence of water stress ($\Psi_o = 0$), root growth is predicted to cease



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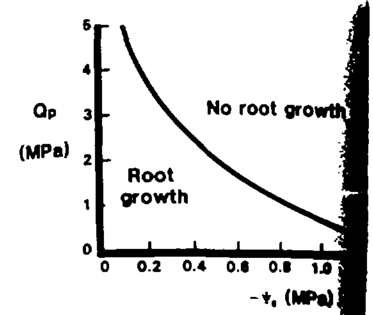

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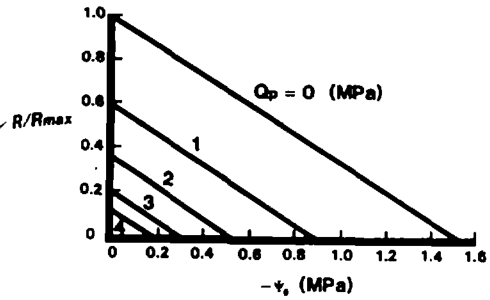

Fig. 1. Values of relative rate of root elongation, R/R_{max}, under combinations of conditions of soil water potential, Ψ_o, and penetrometer strength, Q_p, predicted from Equation (29).

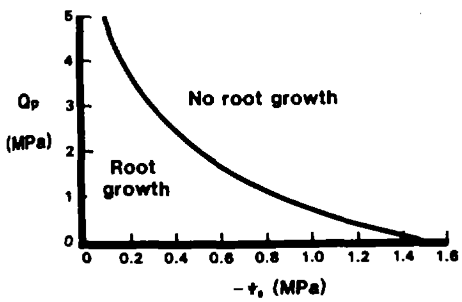

Fig. 2. Curve indicates combinations of values of soil water potential, Ψ_o, and soil penetrometer strength, Q_p, at which root growth will cease as predicted from Equation (29).

at $\sigma = 1/0.85 = 1.18$ MPa. This would correspond to the maximum growth pressure, σ_{max}. Therefore, Equation (27) may be written as

$$\frac{R}{R_{max}} = 1 - \frac{\Psi_o}{\Psi_w} - \frac{\sigma}{\sigma_{max}}, \tag{28}$$

where Ψ_w is the wilting point water potential of the plant species. Equation (28) may be combined with Equation (16) to give

$$\frac{R}{R_{max}} = -\frac{\Psi_o}{\Psi_w} + e^{-0.6931(Q_p/Q_{1/2})}, \tag{29}$$

which gives the relative rate of root elongation in terms of the commonly-measured soil properties: water potential and penetrometer strength. Fig. 1 shows values of R/R_{max} under various combinations of water stress and soil penetrometer strength for a plant with $Q_{1/2} = 1.3$ MPa and $\Psi_w = -1.5$ MPa as predicted by Equation (29). This equation also predicts that root growth will cease at less negatives values of Ψ_o in strong soil. Root growth ceases when the osmotic adjustment of Ψ_i reaches its limit under the combined influence of Ψ_o and

Table 1. Experimental values for maximum rate of root elongation, R_{max}, maximum growth pressure, σ_{max}, and soil penetrometer pressure, $Q_{1/2}$, which halves the rate of elongation of plant seminal roots

Plant species	R_{max} (mm day^{-1})	σ_{max} (MPa)	$Q_{1/2}$ (MPa)	Ref
Bean (*Faba vulgaris* L.)	—	1.08	—	6,16
Cotton (*Gossypium hirsutum* L. cv. Empire)	85	—	0.72	18
Cotton (*Gossypium hirsutum* L. cv. Coker 413–68)	—	0.92	—	19
Cotton (*Gossypium hirsutum* L. cv. Coker 413–68)	—	1.1	—	5
Cotton (*Gossypium hirsutum* L. cv. Sicot 3)	—	0.29	—	15
Maize (*Zea mays* L.)	—	1.45	—	6,16
Maize (*Zea mays* L. cv. United 106)	26	—	1.3	13
Pea (*Pisum sativum* L. cv. Brunswick)	—	1.31	—	19
Pea (*Pisum sativum* L. cv. Meteor)	—	—	2.03	7
Pea (*Pisum sativum* L.)	24	—	—	9
Pea (*Pisum sativum* L. cv. Onward)	35	—	—	4
Pea (*Pisum sativum* L. cv. Brunswick)	—	1.2	—	5
Pea (*Pisum sativum* L. cv. Greanfeast)	—	0.50	—	15
Peanut (*Arachis hypogaea* cv. Virginia bunch)	65	1.16	1.91	19
Ryegrass (*Lolium multiflorum* cv. 522)	—	—	1.39	7
Sunflower (*Helianthus annuus* L. cv. Hysun)	—	0.24	—	15
Tomato (*Lycopersicon esculentum* cv. Potentate)	—	—	1.48	7

σ. However, soil strength will have no influence on the ability of a root to dry the soil down to Ψ_w behind the elongation regions of the root tips. Combinations of conditions where root elongation are predicted to cease are shown in Fig. 2.

It should be noted that, in practice, root elongation may decrease at small values of $|\Psi_o|$ as the soil becomes saturated and anaerobic. Close to the wilting point or at high levels of mechanical stress, on the other hand, roots may be unable to osmoregulate fully, and the above equations may not describe the behaviour accurately. Also, under conditions of high evapotranspiration, plant water status may be controlled by the ability of the soil to transport water to the root, and the effective value of Ψ_o may be significantly more negative than the mean value of Ψ_o of the soil.

Some experimental values of R_{max}, σ_{max} and $Q_{1/2}$ are presented in Table 1. It is not known why the values of σ_{max} obtained by Misra *et al.*[15] were smaller than those obtained by other authors. Unfortunately, there is no single plant species for which a complete set of data has been measured using the same batch of seed from the same cultivar. Future research should attempt to remedy this as it would provide a much better test of the above relationships than is possible at present.

It is not essentila to use penetrometers to estimate growth pressures, σ. Application of soil mechanics theory, as developed in Civil Engineering, can enable σ to be estimated as functions of soil shear strength, friction, compressibility, *etc.*[3,8,14]. These analytical approaches require a

large data set and usually in
more accurate approach invol
finite-element analyses[17].
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Further development of ou
growth will require additiona
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range of plant species and soil
its limitations, will continue

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large data set and usually involve several simplifying assumptions. A more accurate approach involves the use of non-linear soil parameters in finite-element analyses[17]. To do this, information is required about the shape of the root tip, which changes with soil strength, and assumptions have to be made about the levels of friction and associated slippage at the interface between the root tip and the soil.

Further development of our understanding of the mechanics of root growth will require additional accurate data relating root growth pressures and penetrometer pressures as in Equation (16), and more measurements of root osmotic potential, Ψ_i, under various combinations of water and mechanical stress. These experiments should be done with a range of plant species and soil types. It seems that penetrometry, with all its limitations, will continue to be used for a long time to come.

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Characteristics of rhiz indigenous to the Ca *Oxytropis maydellian*

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Received 3 January 1986. Rev

Key words Arctic Astragal
Symbiosis

Summary Forty-eight strains
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United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-78-094
May 1978

Research and Development

PB 285 228

EPA

A Study of Vegetation Problems Associated with Refuse Landfills

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-285 223

A Study of Vegetation Problems Associated with Refuse Landfills

Cook Coll, New Brunswick, N J

Prepared for

Municipal Environmental Research Lab, Cincinnati, Ohio Solid and Hazardous Waste Research Div

May 78

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TECHNICAL REPORT DATA
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4. TITLE AND SUBTITLE: A Study of Vegetation Problems Associated with Refuse Landfills		5. REPORT DATE: May 1978 (Issuing Date)
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7. AUTHOR(S): Franklin B. Flower, Ida A. Leone, Edward F. Gilman, and John J. Arthur		8. PERFORMING ORGANIZATION REPORT NO.
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15. SUPPLEMENTARY NOTES

Robert E. Landreth, Project Officer 513/684-7871

16. ABSTRACT

A mail survey of about 1,000 individuals, was conducted for the purpose of determining the status of landfill vegetation growth. Of the 500 people responding, about 75 percent reported no problems. Twenty-five percent reported problems on landfills and 7 percent reported problems with vegetation adjacent to landfills. Site visits were selected to represent the nine major climatic regions as defined by Trewartha. About 60 individual landfills were visited, and comparisons of the quality of soil atmospheres were made in the root zones of healthy specimens and individuals of the same species that were dead or dying. Comparisons of soil quality were made likewise. Where landfill gases were high in concentration, elevated concentrations of available ammonia-N, moisture and the trace elements iron, manganese, copper, and zinc were found--changes similar to those found in flooded soils. Also, high soil temperatures were found associated with landfill gases in a number of cases. Landfill vegetation growth conditions were generally similar for most of the climatic regions visited.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Methane Carbon Dioxide Vegetation	Solid Waste Management Sanitary Landfill Landfill Gas	13B

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TABLE J-10. (continued)

LIST OF ABBREVIATIONS

Mg	--	Magnesium
P	--	Phosphorus
K	--	Potassium
Ca	--	Calcium
NH_3-N	--	Ammonia-nitrogen
NO_3-N	--	Nitrate-nitrogen
H_2O	--	Moisture
O.M.	--	Organic Matter
Fe	--	Iron
Mn	--	Manganese
Cu	--	Copper
Zn	--	Zinc
B	--	Boron
Fe/Mn	--	Iron/Manganese
C.	--	Conductivity

EPA-600/2-78-094
May 1978

A STUDY OF VEGETATION PROBLEMS ASSOCIATED WITH REFUSE LANDFILLS

by

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Grant No. R 803762-02

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FOREWORD

The Environmental Protection Agency (EPA) was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollution discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communication's link between the researcher and the user community

The ultimate use of refuse landfills involves the planting of vegetation. The problems of growing deep-rooted vegetation over former landfills has been studied through literature surveys, a mail survey of the United States and its possessions, and by on-site evaluations of vegetation growth at former landfills within the major climatic zones of the continental United States and Puerto Rico. It was the purpose of these studies to determine the geographic extent of problems associated with vegetating completed landfills throughout the United States.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

A mail survey of about 1,000 individuals, presumed to be knowledgable of the vegetation associated with operating and completed landfills throughout the continental United States and territories, was conducted for the purpose of determining the status of landfill vegetation growth. Of the 500 people responding, about 75 percent reported no problems. Twenty-five percent reported problems on landfills and 7 percent reported problems with vegetation adjacent to landfills.

Using reports received through the mail survey, landfills for site visits were selected to represent the nine major climatic regions as defined by Trewartha. About 60 individual landfills were visited, and comparisons of the quality of soil atmospheres were made in the root zones of healthy specimens and individuals of the same species that were dead or dying. Almost invariably, where soil atmospheres contained high concentrations of landfill gases, vegetation was adversely affected.

Comparisons of soil quality were made likewise. In almost all cases where landfill gases were high in concentration, elevated concentrations of available ammonia-N, moisture and the trace elements iron, manganese, copper, and zinc were found--changes similar to those found in flooded soils. Also, high soil temperatures were found associated with landfill gases in a number of cases.

Landfill vegetation growth conditions were generally similar for most of the climatic regions visited. Those in the desert area, however, were found to have somewhat lower landfill gas concentrations than the others--possibly due to dry conditions.

This report was submitted in fulfillment of Contract No. R 803762-02 by Rutgers University under the sponsorship of the United States Environmental Protection Agency. This report covers the period May 15, 1975 to May 14, 1977, and the work was completed as of June 15, 1977.

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ACKNOWLEDGMENTS

The cooperation of the New Jersey Cooperative Extension Service personnel, particularly Dr. Spencer H. Davis, Jr., Specialist in Plant Pathology, and Dr. Roy Flannery, Specialist in Soils, is greatfully acknowledged. The authors also wish to express their indebtedness to the hundreds of individuals representing federal, state, county, and municipal governmental agencies, as well as private individuals, who responded to the mail survey and assisted in planning and executing the site visits. We would also like to acknowledge the assistance of the following: Cook College students Heather Boyd, Deborah Flower, and Michael Telson, and research technicians Tirza DeVries and Dr. Jeanette Mohamed. Finally we wish to thank all the Cook College staff who so kindly gave their assistance.

SECTION I

INTRODUCTION

Sanitary Landfill has been demonstrated to be the least expensive environmentally acceptable means of waste disposal available to date, purportedly possessing the attributes of neatness and safety in addition to the relatively low cost. Whereas such sites may have originally been located at considerable distances from residential areas, rapid urban and suburban development in the United States has caused many once remote dumping grounds to be within developed areas. As such they provide an attractive source of much needed land for many purposes. Although conversion to recreational areas or other non-structural usage has long been considered an acceptable end for completed landfill sites, the urgent need for space and for increased tax revenues has caused many municipalities to eye completed landfills for commercial use as well. In rural areas, intensifying land use has resulted in attempts to use completed landfills for growing commercial crops.

Regardless of the ultimate utilization of the landfill, certain serious disadvantages are inherent, not the least of which are ecological upsets due to leaching of infiltrates and gases into groundwater, pollution of water supplies, the production of toxic and explosive gas mixtures from anaerobic microbial decomposition of the organic matter present, and surface settlement. High ground temperatures have also been reported in the cover material of some completed refuse landfills.

The state of New Jersey, with a population of approximately $7\frac{1}{2}$ million, has experienced vegetation growth problems on and around refuse landfills. The state is currently serving as the repository for solid waste from a population of approximately 10 million. There are some 300 active landfill sites in New Jersey comprising approximately 10,000 acres that predictably will become filled in the next few years. There are also in existence within the state some 150 completed landfills, many of which have already been converted to some of the aforementioned uses. Landfills completed up to World War II were shallower and contained less organic matter than the present ones possibly as the result of more coal ashes, more open burning, and less wastage during those earlier times. Since World War II the amount of disposable waste has risen considerably with a concomitant rise in content of biodegradable material. It is believed that the changing character of the waste in landfills and the increasing need to develop former landfills for new land have helped make vegetation deaths more noticeable. More than half a dozen landfill sites in New Jersey were known to have experienced this problem.

With the death of vegetation associated with landfills well documented in New Jersey, it was desirable to see if similar situations existed in other parts of the United States and to examine possible causes of these vegetation growth problems. The survey of the quality of landfill vegetation growth consisted of a mail survey of the United States followed by on-site visits to former landfills in all the major meterological regions found in the 48 continental states and Puerto Rico.

SECTION II

CONCLUSIONS

1. A mail survey of some 1,000 persons assumed to be knowledgeable of plant growth status on or adjacent to completed landfills showed fully 75 percent of those who responded as unaware of the problems associated with vegetating completed landfills.

2. Site visits to some 60 completed landfills within nine climatic regions of the United States generally revealed a high negative correlation between plant growth and concentrations of methane and/or carbon dioxide in the root atmospheres.

3. Little variability in the magnitude of landfill gas production and consequent vegetation damage was observed among the different climatic regions, except for the arid area (southwestern Arizona) where concentrations of combustible gas and carbon dioxide were found to be somewhat less than in the eight other regions. This was presumably due to the lack of rainfall.

4. A number of woody species including American linden, American elm, Japanese spreading yew, and sugar maple were found to be particularly sensitive to landfill conditions.

5. The degree of sensitivity to landfill conditions among the woody species closely paralleled relative tolerance of these species to flooded or water-logged soils.

6. Soil characteristics, other than atmospheric quality modified by the presence of anaerobically produced landfill gases, included content of moisture and available ammonia-nitrogen, iron, manganese, zinc, and copper--all of which increased significantly in landfill gassed soils. Increased availability of these elements is believed to be due to the highly reduced conditions in the soils and the activity of anaerobic microorganisms. Soil pH tended to approach neutrality in gassed soils due to the presence of organic acids produced during anaerobic decomposition of the buried refuse.

7. Where attempts were made to prevent the migration of landfill gases into plant root zones through the use of impermeable barriers, vertical venting or gas extraction systems, or through planting in mounds of earth placed atop landfills, plants appeared to have a better chance of survival.

8. Occasionally high soil temperatures (up to 60°C) adverse to vegetation growth were found associated with landfill gases in the soil.

SECTION III

RECOMMENDATIONS

1. The lack of awareness of landfill managers of the problems attendant on establishing vegetation on landfill sites indicates the need for education along these lines. It was also found that in about one third of the cases there were discrepancies between conditions reported in the mail survey and those found in on-site visits to the landfills.

2. The variability in landfill gas tolerance among species suggests the need for research aimed at screening plant species for their adaptability to landfill gases.

3. The similarities between soil characteristics in landfill cover soils and in water-logged soils suggests the use of flood resistant species for landfill plantings.

4. The lack of understanding of the precise role of specific landfill gases in causing plant deterioration suggests the need for research aimed at clarifying this situation.

5. To grow healthy vegetation, landfill gases should be prevented from entering the plant root atmospheres.

however, in later study, the 'ary trees died - they couldn't get enough moisture!

SECTION IV

LITERATURE SURVEY

GAS PRODUCTION IN REFUSE LANDFILLS

The composition of landfill refuse varies considerably depending on its origin be it municipal, industrial, incineration material or sewerage sludge. The organic content of solid waste collected from homes, schools, commercial establishments and industries generally ranges from 50 to 75% on a weight basis. Most of these organics are biodegradable and can be broken down into simpler compounds by both aerobic and anaerobic micro-organisms. The rate at which this occurs is reported to be a function of (a) permeability of cover material (b) depth of garbage (c) amount of rainfall (d) moisture content of the refuse (e) putrescibility of the refuse (f) compaction (g) pH and (h) age of the landfill (1, 2,).

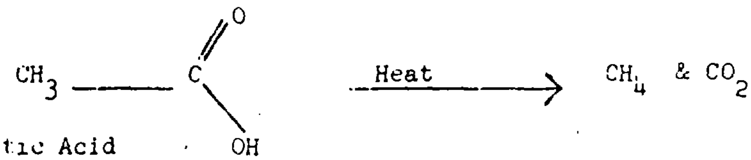
When the refuse is initially deposited in the landfill, there is enough oxygen present to support a population of aerobic bacteria. This stage lasts from one day to many months (3). The literature indicates CO_2, NH_3, and H_2O to be the principle products formed in aerobic decomposition (4).

The depletion of soil oxygen results in a decrease in the aerobic and an increase in the anaerobic population. During the anaerobic stage of decomposition two phases have been identified, a non-methanogenic stage followed by a methane-producing stage.

During the non-methanogenic stage, organic matter is reduced, in the presence of water and extracellular enzymes produced from bacteria, to smaller soluble components which include fatty acids, simple sugars, amino acids and other light weight compounds (5). Further breakdown of soluble compounds in the absence of oxygen produces H_2, CO, NH_3, H_2O, CO_2 and organic acids (probably acetic acid) (5, 6, 7)

During the methanogenic stage, CO_2 and CH_4 are the principle gases produced. They originate from two reactions carried out by a bacterium called <u>Methanobacterium</u>(6). In the first reaction, the CO_2 produced earlier in the decomposition is reduced through the addition of hydrogen to form methane and water. The second reaction utilizes the acetic acid produced during the non-methanogenic stage. Acetic acid is cleaved in the presence of heat to form methane and carbon dioxide. These two reactions are represented below:

(1) $CO_2 \xrightarrow{4H_2} CH_4$ & $2\,H_2O$ & Heat

(2) 

Acetic Acid

Various other gases reportedly produced in the anaerobic environment of the landfill include ethane, propane, phosphine, hydrogen sulfide, nitrogen and nitrous oxide (8,9,10,11,5). A literature search of studies concerning the effects on vegetation in response to the presence of these six gases in the root zones produced a single article from Japan(12). Hydrogen sulfide, which is produced from the bacterium Desulfovibrio desulfuricans in alkaline conditions (13), was reported to have caused lower root respiration rates and a decrease in soil nematode population (14).

In addition to the methane-producing bacteria mentioned above, there exists a bacterium, Pseudomonas chromobacterium, which utilizes methane during its metabolism. It oxidizes methane, producing carbon dioxide and water (15). Since oxygen is required for this reaction, these bacteria will generally be found near the upper surface of the landfill.

During the oxidation of methane, oxygen in consumed. This raises a question of whether or not the oxygen concentration is a limiting factor in this reaction. Hooks points out that these organisms can function at soil atmospheric oxygen concentrations as low as 1%. However, at this low concentration, incomplete oxidation causes formation of such intermediate side products as methanol, formaldehyde and formic acid (15).

During anaerobic decomposition, the possibility exists for production of a wide range of gases and liquids. However, the literature indicates CO_2, H_2, CH_4, H_2S, and N_2 to be the predominant gases with CO_2 and CH_4 making up the largest portion of the soil gas atmosphere. There has been a considerable amount of work done concerning the effects of excess CO_2 in the root zone on different plant species. In 1914, Noyes saturated soil around tomato and corn plants with CO_2(16). Both species died within two weeks, but there was no irreversible damage to the soil.

A good deal of variation in tolerence between species has been found. Cotton seedlings grown in hydroponic solutions (17) were able to exhibit optimum growth with 10% CO_2 present, provided at least 7.5% O_2 was also present. Thirty to 40 percent CO_2 in the root zone of cotton seedlings was found to severely reduce root growth in hydroponic solutions. Red and black raspberry (18) were killed when their roots were exposed to 10% CO_2.

Norris, Wiegand, and Johanson (19) in 1959 exposed excised onion root tips to CO_2 concentrations above that normally found in soil atmospheres. They concluded that an observed decrease in respiration rate was due to permanent damage to the root cells caused by the lowering of the intercellular pH by dissolved CO_2.

There are various factors influencing methane gas production. The parameters most commonly reported are refuse moisture content, temperature and pH. Probably the major factor is refuse moisture content. Ramaswamy (20) and Songonuga (21) found that methane gas production rates increased with refuse moisture content, a maximum production occurring at moisture content of 60 to 80% wet weight. Farquhar and Rovers (6) report maximum methane production when refuse is near the saturation point. An experiment carried out by Merz and Stone (22) concluded that methane gas production increased with the addition of surface irrigation water. Ludwig (23) found that at one of two sites in California methane production increased after a heavy rainfall.

It is reported that refuse moisture content too low to support continuous gas production in a landfill may be in the range of 30 to 40% (22). This condition may exist in certain areas of the United States such as the dry southwest, where rainfall and relative humidity are very low.

Temperature has also been described as a limiting factor in methane gas production. Aerobic conditions invariably produce higher temperatures than anaerobic (24,22). Three separate articles have reported optimum temperatures for methane production ranging from 30°C to 37°C. Kotze et al (7) report 37°C to be the optimum temperature for methane gas production in the mesophilic stage of sewage sludge decomposition. Dobson (25) and Ramaswamy (20) say maximum gas production occurs at 30°C and 35°C respectively. All found that deviations from the optimum temperature resulted in decreased methane production rates.

The optimum pH for methane production during anaerobic decomposition of sewage sludge is very near 7.0 (6). As deviations from this optimum are encountered, gas production is decreased. Extremely high pH may exist in the refuse because of the presence of alkaline materials, whereas low pH levels can result in inhibition of methane production with the concomitant formation of organic acids (6).

One parameter which was measured in a number of studies was the effect of excessive infiltration on methane production. When large amounts of water were added to a lysimeter filled with refuse so that the saturation point was almost reached, methane production was inhibited; however, CO_2 continued to be produced. This response was attributed to the positive oxidation-reduction potential of rain water suppressing the activity of methanogenic bacteria which require a negative oxidation-reduction potential (26).

HISTORY OF PROBLEMS IN VEGETATING LANDFILLS

Conversion to recreational areas or other non-structural usage has been considered an acceptable end for completed landfill sites and, in rural areas, intensifying land use has resulted in attempts to use completed landfills for growing commercial crops (27, 10, 28, 29, 30, 31, 32, 33).

The serious disadvantages for adequate vegetation growth inherent in landfill sites have been enumerated namely, the production of toxic gas mixtures from anaerobic decomposition of organic matter present, the leaching of infiltrates and gases into ground water supplies, and the high ground temperatures (34, 10, 35).

In spite of predictable negative success in utilizing landfills for the support of vegetation, many reports of success or proposals for transforming barren former refuse sites into luxuriant vegetated areas are appearing in the literature and in the press (36, 37, 38, 39, 32, 40).

In July, 1972 an article by Duane(41) applauding the construction of golf courses on completed sanitary landfills cited the successful use of such tree species as Japanese black pine, London plane, thornless honey locust and Russian olive for beautifying the sites. In 1973, an anonymous article entitled "From Refuse Heap to Botanic Garden' appeared in Solid Wastes Management magazine describing the transformation of an 87-acre landfill in Los Angeles that had the distinction of being one of the world's first such phenomena (42).

A catalogue published in 1973 describing hybrid poplars bred by a Pennsylvania nursery cites a particular hybrid which supposedly was grown successfully on a landfill site at Fort Dix, New Jersey (43). In that same year, a brochure was published by the Caterpillar Tractor Company describing and displaying in lavish color various successfully vegetated golf courses and parks in Mountain View, California; Ancka, Minnesota; Baltimore County, Maryland; Long Island, New York; Alton and Chicago, Illinois (44). In 1974 a news item in the Sun-Star of Merced, California described a 5-acre park whose new grass and trees would be aided in growth by "the proximity to the refuse which will provide needed nutrients" (45).

Few problems if any were either observed or anticipated in achieving these spectacular results with the exception of the report of root damage to large trees and shrubs at the Los Angeles Botanic Garden site.

At the same time, various investigators were experiencing difficulties in growing vegetation at similar sites. In January 1969, Professor F. Flower and associates of Rutgers University in New Brunswick, New Jersey (46), responding to a complaint of vegetation death on private properties adjacent to a landfill in Cherry Hill Township observed dead trees and shrubs of the following species: spruce, rhododendron, Japanese yew, azalea, dogwood, flowering peach, brush dogwood, Scotch broom, arborvitae, Douglas fir, and lawn grasses. Testing of the soil with appropriate equipment disclosed high concentrations of carbon dioxide and explosive gases. The conclusion reached was that the trees and shrubs could have been killed by displacement of oxygen from their root zones by lateral movement of the gases of refuse decomposition.

This site was visited periodically from 1969 to the present time, soil gas was tested for explosive gas content and vegetation around the homes evaluated for gas effects (47).

Subsequent visits were made to the site on March 12, March 18, and March 31, 1975 (48). Examination of the landfill area on which a park had been constructed revealed that many trees had been planted over the area the previous fall. The species included sweet gum, red oak, Japanese poplar, white pine, Scotch pine and fir among others. Some of the trees had been destroyed by being pulled out by their roots. The holes remaining were rather shallow indicating that plantings were not made at a great enough depth.

The needles on some evergreen were brown indicating little likelihood of survival.

Gas vents had been installed consisting of plastic pipes with holes placed vertically in the ground.

Leachate was found in some spots. Grass growth throughout the park was spotty; in some areas it grew well, whereas in other areas, very poorly.

A return visit to the site on May [illegible], 1975 ([illegible]) was made to evaluate the quality of the vegetation which had been planted over the area. Most of the trees were still living with the exception of a large number of Austrian pines and Scotch pines. The firs, white pines, and deciduous trees in most cases were doing very well.

Ground gas samples were taken and in most cases gas was not encountered until a depth of 1[illegible] to 25 inches was reached. In only one case was there evidence of high combustible gas level in the root zone of a deciduous tree and that tree had died. Vetch, clover, grasses and weeds covered much of the area; some spots were noted to be barren. Ground gas was found very close to the surface in some of the latter areas. Signs of leachate were also noted at a few locations.

Checks for combustible gas were made in several of the vertical venting pipes, results of which indicated that these pipes were venting the gases from the landfill. It was concluded that a hard layer at the base of the [illegible] to [illegible] feet of cover material had successfully sealed off the combustible gases from the root zone of trees, forcing the gas to move laterally to the venting pipes whence they were being dispersed to the atmosphere. The vents probably reduced underground lateral migration of gases away from the landfill, although a single check in this area showed combustible gas to be present.

In 1972, the Rutgers contingent made a visit to the peach orchard of the De Eugenio brothers in Glassboro, New Jersey which bordered on a completed landfill, where approximately 50 peach trees had died (47). Upon completion of the landfill, the growers had hoped to plant additional peach trees on the filled area. Examination of the soil atmosphere revealed high concentrations of carbon dioxide and explosive gases in the orchard area.

The conclusion was that carbon dioxide and methane from the anaerobic decomposition of organic matter had moved laterally from the landfill into the orchard area. The sealing of the surface of the landfill with a soil cover had probably been sufficient to prohibit the free passage of gases vertically out of the landfill, therefore, they had taken an easier route laterally into the soil in the root area of peach trees adjacent to the landfill.

A return visit was made to the De Eugenio orchard on March 18, 1975 (50). There had been further peach tree death from lateral migration of the landfill gases. No corrective measures had been taken.

In May, 1973 the Rutgers group visited the Hunter Farm in Cinnaminson, New Jersey where previous visits had confirmed that combustible gases from an adjacent landfill had encroached upon the farmland and injured crops (47). A venting system of perforated PVC pipes had been installed at the interface of the landfill and Hunter Farm land. Samples taken from the permanent gas sampling stations at Hunter Farm revealed combustible gas extending 200 feet into the Hunter Farm field. It was not possible at the time to determine whether any improvement in gas migration had been effected by the venting system.

Hunter Farm was again visited in December, 1974 when fields planted with rye were growing poorly (47). Gas checks revealed that combustible gases were present in the area of new vegetation injury and that migrating gases were now reaching 600 feet from the nearest edge of the landfill. Apparently the venting was inadequate.

Another trip to Hunter's Farm was made in July, 1975 when corn and sweet potato were found to be growing poorly in areas where combustible gas concentration was high. At this time gas migration was found at 800+ feet from the edge of the landfill (77).

On May 14, 1973, the Rutgers group visited Sharkey's Landfill in Parsippany-Troy Hills, New Jersey to estimate its potential for supporting vegetative cover and to examine field test plots set out by a county agent (51). It appeared that grass seeding had been attempted; however, grass seemed to be growing well over only small areas of the fill. Numerous pools of oily leachate were observed, many with gas bubbles breaking the surface.

Samples of soil gas revealed high concentrations of combustible gases. In the few areas where vegetation seemed to be growing well, there was little, if any combustible gas in the root zone.

The general consensus on the possibility of successful vegetation appeared to be that only shallow rooted species such as grasses would be expected to thrive over most of the area. In some spots devoid of combustible gas it might be possible to grow deeper rooted vegetation.

A communication from the county agent on June 3, 1975 revealed that clover, vetch, lespedeza and weeping love grass were doing well on the landfill (52).

On January 28, 1974 the Rutgers group visited an 18-acre refuse landfill which was the proposed site for a high-rise apartment project. At the north end of the landfill, a bank had been constructed three years previously on pilings (53). Ground settling, gas odor and vegetation death were observed on the bank property. Checks for soil gas revealed high concentrations of combustible gases in the areas of vegetation death.

At the same time that the Rutgers investigations were going on in New Jersey other investigators in this country and abroad were also reporting lack of success in growing vegetation on or near landfills.

In 1972, Kutsuma found a chestnut blight in the area of a landfill in the Toma River Valley in Japan, due to a high carbon dioxide and methane content (54) and the following year Ueshita, Kuwayama and Saita (55) reported the death of unspecified tree species which had been planted on a landfill in Aichi Prefecture.

In 1972, a scientific study of the growth response of four species of pine on simulated landfills was conducted by Cremer (56) in fulfillment of requirements for an advanced degree at Yale School of Forestry. Preliminary results indicated that two of the species, Monterey pine and Pitch pine, were growing poorly on the simulated landfill plot whereas Austrian pine and Jack pine appeared to be unaffected.

In 1973 a report from Toronto, Canada (57) blamed ethylene gas from a landfill for vegetation mortality.

In the same year an anonymous publication (45) issued in Ontario, Canada discussed the killing of vegetation by gases escaping from a sanitary landfill in Mississauga, Ontario.

Various other communications (34, 58, 59, 30) during the past year have reported further observations of vegetation problems on former landfills ascribing the problem to methane gas, high soil temperatures, and/or insufficient depth of cover. Among the reports was one describing injury to corn crops on landfilled trenches as compared to normal growth on inter-trench nonlandfilled areas in Connecticut (60).

The variability in results from efforts to establish vegetation on former landfill sites is apparently due to variability in certain landfill characteristics such as type and amount of solid waste, depth of cover, construction and grading of the fill; certain regional meteorological conditions, such as temperature, relative humidity and rainfall; soil characteristics such as composition, texture, ability to retain moisture, nutritional characteristics; adaptability of plant species to landfill conditions, and planting and maintenance techniques to overcome unfavorable landfill conditions (61, 62, 63, 64, 65, 35).

EFFECTS OF LANDFILL GASES ON VEGETATION

Illuminating Gas

Included among the many decomposition gases from landfills produced during the anaerobic breakdown of organic matter are CH_4, H_2, NH_3, H_2S, CO_2, N_2, C_2H_4 and CO (66). Mechanisms have been brought forth to show how these products are formed from their precursor macromolecules. The literature describing the effects of these gases on vegetation is very sparse possibly due to the lack of concern. However, as far back as 1807, problems concerned with trees injured by illuminating gas accidently leaking into the soil, may be said to have commenced when the first public street lighting system was installed in Pall Mall, London (67).

One may ask what illuminating gas has to do with these decomposition gases and their effects on vegetation. Table 1 gives the composition and some representative concentration of the constituents of illuminating gas. A quick glance at this chart will bring forth immediately, the importance of studying the effect of illuminating gas on vegetation. The gases CH_4, CO_2, N_2, C_2H_4 and CO comprise the majority of the constituents of manufactured illuminating gas.

TABLE 1. APPROXIMATE PERCENTAGES OF SUBSTANCES COMPRISING MANUFACTURED ILLUMINATING GAS

Substance	% Composition by Volume
Ethylene (C_2H_4)	3
Acetylene (C_2H_2)	5
Benzene (C_6H_6)	
Butylene (C_4H_8)	
Propylene (C_3H_6)	
Carbon Monoxide (CO)	33%
Ammonia (NH_3)	Less Than 5%
Cyanogen compounds*	
Hydrocyanic Acid* (HCN)	
Hydrogen (H_2)	33
Carbon Dioxide (CO_2)	1.5
Oxygen (O_2)	1
Nitrogen (N_2)	6
Methane (CH_4), ethane (C_2H_6), propane (C_3H_8)	12

*Most of these have been removed from manufactured gas by a process called "scrubbing".

NOTE: This table was abstracted from bibliography reference #70.

Ethylene (C_2H_4) is of special interest although it has to date rarely been considered a limiting factor by authorities trying to establish vegetation on completed sanitary landfills. Smith and Restall (68) showed that ethylene was produced in anaerobic soil by biological activity and not by chemical action. In a simulated anaerobic soil, when O_2 concentrations fell to zero, ethylene production increased. Total evolution was related to organic matter content and soil temperature. A temperature of 35°C produced the maximum ethylene evolutions.

Methane production was also reported to be optimum at 30°C and 35°C by Dobson and Ramswany respectively (25, 20). Smith and Harris (69) report that under anaerobic conditions, if no losses of ethylene occur, its concentration in soil atmosphere can reach or exceed 20 p.p.m. (0.002%) in widely differing soil types in the United Kingdom. These concentrations are in considerable excess of those which have been found to cause severe reductions in the extension of seminal root axes in temperate cereals (68). Barley, which was the most sensitive of the cereals studied, suffered 50% reduction in size after three days exposure to 1 p.p.m. of ethylene in soil and 80% at 10 p.p.m. The corresponding figures for rye were 25% and 40%. Oat and wheat sensitivities were between barley and rye. When CO_2 concentrations in the soil were varied, little change in the cereals' response was noted.

Because of the above experiments, it is appropriate to consider ethylene as a possible toxic component of illuminating gas. The late 1800's and early 1900's produced much concern over escaping illuminating gas and the injury it caused when in contact with the root system of various shade trees and ornamentals. The historical portion of Crocker and Knight's (71) study on carnations and illuminating gas described much of the previous work done in Germany in the late 1800's. According to Crocker and Knight Kny was one of the first to test the injury experimentally. He used three sound trees in the Berlin Botanical Garden, each about twenty years old--one maple (Acer) and two lindens (Tilia). Gas pipes were laid 84 cm. underneath the soil where these trees were to be planted. On July 7 illuminating gas was passed through the pipes beneath the maple at 12.9 cu.m./day and beneath the two lindens, 11.7 and 1.6 cu.m/day respectively. First a euonymous (E. europea) bush near the maple died, followed by defoliation of the maple leaves on September 1. An American elm near by showed injury also. On September 30, the first linden began to show signs of injury, and by October 12 it had lost all its leaves The second linden had lost its leaves by October 19. A blue discoloration concentrated in the stele showed up on close examination of cross sections of the roots one-half inch in diameter or larger. The lindens both produced foilage the following spring; however, it was bleached and very stunted. The maple, elm, and euonymous bush showed no signs of life.

Spath and Meyer (71) passed 1 cu.m. of gas daily through wooden pots each containing one tree. Platanus, silver poplar, American walnut and Ailanthus were killed; maple and horse chestnut were severely injured, and a linden showed no injury. The leaves of the injured trees were a pale green or yellow and most of the younger roots were dead. These investigators concluded that trees are far less sensitive to gas injury during the winter months when the sap is not flowing than during the growing season. The above two experiments suggest that linden is more resistant to injury brought about by illuminating gas than any other mentioned species.

Bohm (71) grew slips of water willow in water through which gas was passed. He found that they produced only short roots and that these soon died, as did the dormant buds. The twigs themselves remained alive for about three months until, as he believes, the reserve food had been exhausted.

In another experiment he found that soil impregnated with gas was very poisonous to plants and for seed put to germinate in it. A draceana planted in such soil died in ten days. Far less injury was shown when a given quantity of gas was in contact with the portions of the plant above the ground than when the same quantity came in contact with the roots by being passed into the soil. He concluded that roots are most sensitive to gas injury.

Wehmer (71) calls attention to a severe case of gas poisoning in Hanover, Germany. Thirteen elm trees along a street showed injuries varying with the distance they stood from a leak in a gas pipe. In late winter a number of them showed brown discoloration of the inner bark, and a falling-off of the bark in very large patches extending up the trunk six feet from the ground. No blue discolorations of the roots appeared as was reported by Kny (71) and other observers (71).

Molisch (71) found that growth in length of roots is retarded by 0.005% illuminating gas in soil gas atmosphere. If uninjured and decapitated roots of corn are grown in illuminating gas, the former are remarkably bent and retarded in their growth in length, while the latter grow almost straight and are comparatively vigorous. Under the influence of the gas the growth in thickness of the roots is increased with the greatest thickening occurring where the bending is sharpest.

Shonnard (71) had exposed potted lemon trees to gas at 1.07 cu. ft./hr. constantly for eight days when he noted exudation of sap in considerable quantity from the trunk and branches, as well as chlorosis and defoliation of leaves. He found gametophytes of certain mosses to be very resistant, suffering very little injury in high concentrations of these gases after two months exposure. Elodea and nittella's older cells were injured to a greater extent than the younger cells, as shown by the plasmolysis of the cells.

Richards and Mac Dougal (72) found that carbon monoxide and illuminating gas retarded the rate of elongation of roots of Vicia faba, sunflower, wheat and rice. Swelling also appeared in the leaf sheaths of wheat, being somewhat more pronounced with illuminating gas than with carbon monoxide. Examination of a root cross section under an appropriate microscope showed that these increases in root diameter were largely due to the enlargement of the cortical cells.

Stone (73) has reported proliferations of tissue at the lenticels of willow slips growing in water which had been charged with illumination gas. He also noted a rapid proliferation of the cambium in stems of Populus deltoides (Quaking Aspen) under the influence of illuminating gas.

Probably one of the most extensive studies carried out to investigate the effects of illuminating gas on vegetation was done by Harvey and Rose (74). This investigation was undertaken with two objectives in mind: 1-to determine some of the effects of illuminating gas on root systems, and 2-to determine whether the chief causes of injury are those constituents of illuminating gas which are readily absorbed by the water film of soil particles or those which remain primarily in the soil interstices. Because previous work had pointed out the "ethylene effect" on trees which were exposed to illuminating gas, Harvey and Rose (74) decided to test this hypothesis. They placed the bare roots of six Vicia faba seedlings inside a large humidified glass bottle into which they pumped illuminating gas. Then, using the same species in soil and exposing the soil to similar concentrations of gas, they produced the same response as observed with the bare roots. Therefore, they concluded that the constituents of illuminating gas which are relatively insoluble in water are responsible for the response in Vicia faba. Ethylene is included as an insoluble gas. This fact further stimulated Harvey et al. to move towards testing ethylene toxicity.

Again, they used Vicia faba and exposed bare roots, as described above, to illuminating gas. In a separate bottle, ethylene, in concentrations corresponding to that in the illuminating gas, was passed around the roots of the same species. From the observations made in these tests the ethylene was considered one of the toxic agents present in illuminating gas.

The concentration of ethylene used here was 0.001% or 10 p.p.m. Barley's growth decreased by 50% at 1 p.p.m. and rye responded to the same concentrations by a 25% decrease (69). In all these cases, the root response to gas exposure was a bending and swelling of the root at this bend.

When the roots of radish, mustard, and tomato seedlings were exposed in a moist-air chamber to illuminating gas for 24, 48, and 72 hours respectively, the responses of the tomato differed from that of the radish and mustard seedlings(74). While the roots of the mustard and radish showed obvious signs of bending and swelling very similar to Vicia faba, the tomato roots grew as straight as normal seedlings' roots. However, swelling of the hypocotyl was evident and was found to be the result of an enlargement of the cortex and phellogen. Close examination of the stele showed no structural differences from that of a control tomato plant. The experiments with ethylene on tomato again gave some evidence that the toxic effect recorded for illuminating gas is due to the ethylene constituents of that gas.

When Catalpa speciosa seedlings were exposed for eight days to illuminating gas piped through the soil at concentrations of 0.05, 0.5, 2.5 and 5%, stems and leaves showed no modifications (74). However, at 2.5 and 5% the roots showed very obvious swelling. When the same species were exposed to ethylene concentrations of 0.002, 0.02, 0.1, and 0.2% which is comparable to the amount of ethylene contained in the illuminating gas used above, the response shown by the 0.1 and 0.2% ethylene was like that shown by 2.5 and 5% illuminating gas. This gave further evidence to the expanding theory that ethylene toxicity is responsible for the response of the root systems to the illuminating gas. This also showed that larger quantities of illuminating gas and ethylene are needed in soil to produce the same response by roots exposed to corresponding quantities of gas with no soil. Possibly the soil is acting as a buffer and is either absorbing or utilizing the ethylene.

When Catalpa seedlings were exposed for twenty-one days to illuminating gas concentrations of 25% (1% ethylene) a swelling of the main root appeared (6). The increase was 2-3 times that of the normal thickness. The epidermis was often cracked and sloughed off in places. Such cracks provide root rotting fungi and bacteria a mode of easy entry into the root. Very serious stunting and even death can result from root rot infections especially when attack is promoted against young seedlings (75).

Ailanthus altissima seedlings were exposed by Harvey and Rose (74) for fifteen days to illuminating gas concentrations of 0.25 and 10%. The 0.25% treatment gave slight swelling of the roots 3-4 cm below the surface, while the 10% treatment produced leaf drop beginning five days after the gassing commenced. By the end of the experiment, all leaves had fallen. When ethylene was used instead of illuminating gas, in concentrations corresponding to the amount of ethylene present in the illuminating gas in the above experiment, very similar responses were observed. The lower ethylene concentration(0.01%) produced negligible swelling while the higher concentration (0.4%) produced swollen top roots and leaf drop, eight days after the gassing started. Through the examination of cross sections of the control plants and gassed plants, it became evident that the stelar region had remained unchanged, while the cortex, extending into the phellogen layer, had increased in thickness, partly through the increase in cell diameter and partly through cell division. This same phenomenon was seen in the gassed tomato and the Vicia faba plants (74).

A number of tests were carried out with Gleditsia (Locust) seedlings (74). Illuminating gas in concentrations up to 33% were used to fumigate the roots. These high concentrations gave leaf drop, but no definite injuries were detected in the root system.

Briefly looking back on the above work brings out an interesting trend in the pattern of damage produced by varying the concentrations of illuminating gas and ethylene gas in the soil. At low concentrations, such as with the radish and mustard experiment and the Vicia faba plants, the response seems to be primarily a swelling of the roots. However, when higher concentrations are provided to the root systems, the response seen in the root system is cracking and sloughing off of the epidermis in Catalpa. Ailanthus and Gleditsia responded to higher concentrations by dropping their leaves.

Harvey and Rose (74) summarize the work carried out by Kosaroff, whose experiments found that the symptoms manifested in the aerial parts of plants due to illuminating gas being passed through the soil were similar to those seen where the plants were exposed to droughty conditions. He further states that injury is not necessarily due to conduction of toxic substances into the leaves; however, this possibility is not to be overlooked. In experiments conducted to determine the effect various transpiration rates had on the plants' response to gas exposure, Kosaroff found that greater evapotranspiration rates produced gas type injury sooner than did lesser rates of evapotranspiration.

A final experiment was conducted by Harvey and Rose (74) with an Ailanthus tree having an 8 cm diameter and a 3.5 meter height. They used many surrounding Ailanthus trees as controls. By placing a glass tube 0.7 meters into the soil and 0.6 meters from the tree, they passed illuminating gas to the roots of this Ailanthus tree. The gas was supplied at a relatively constant rate starting on July 3. The first symptoms of injury were manifested on July 14. The leaves of some of the young shoots growing on the side of the tree where the gas entered the soil, showed signs of wilting. Three days later these leaves and others shriveled and died, but remained attached to the branches. In the middle of September, the leaves which were apparently unaffected initially, began to shrivel and fall. This tree had lost all its leaves much sooner than the nearby controls. In our field work we have observed black cherry (Prunus serotinia) and black oak (Quercus velutina), apparently killed by landfill decomposition gases, whose leaves had shriveled and still remained hanging on the branches.

In the early 1900's quite a number of articles were written, which reported and described illuminating gas kill of vegetation. Two of the more in depth set of observations were made by members of the Massachusetts Agriculture Experiment Station in 1907 and 1913. In both cases observations were made on a number of trees over an extended period of time beginning with the time of first known gas exposure. Some of their results are discussed below.

Stone (75) reports that the poisonous properties of illuminating gas are largely confined to the numerous products which are absorbed by the soil moisture in small quantities, taken up through the roots and translocated through the tissue. This is in conflict with Harvey and Rose (74) who carried out a controlled experiment showing quite conclusively that the gases present in the interstitial spaces in the soil were responsible for the toxic effect of the gas on vegetation. Stone gives no data for his statement. Stone further states that these substances are to be found in the tissue; however, the response differs between species and even with different parts of the plant.

An anonymous report (66) by the Massachusetts Agriculture Experimental Station describes gas injury in two classes: first incipient cases, then pronounced cases. During observation of the incipient cases the bark has been seen peeling off in very large strips, up to 6 feet long in American elm (66) and 2.5 feet long in quaking aspen (Populus deltoides) (73). The bark on the sides of these cracks was bulged out considerably and on closer examination it was shown that a thick layer of soft parenchymous tissue extended into the wood for a considerable distance. This abnormal tissue was formed outside of the cambium from which it seemed to have been derived. Remember that Harvey and Rose (74) observed A. altissima leaves turning yellow first, then dropping off. The leaves farthest from the source of water, i.e. those at the top of the tree and the ends of the branches, have been observed to be the first leaves to show signs of injury. These are the leaves which characteristically will be the first to show signs of water deficiency. It is the work by Harvey and Rose (74) and others (67) which leads to the belief that root damage at least plays a small role in the yellowing of the leaves farthest from the roots and water supply.

Following the initial injury to the foliage are characteristic changes in the wood and bark of the tree as was briefly mentioned above. The first symptoms appear as a drying of the cambium and other tissues outside the wood or xylem. Later these tissues (cambium, phloem, and cortex) turn brown and disintegration follows. These abnormal conditions first take place in the roots, but Stone states that later, as translocation proceeds, the poisonous constituents may be detected in the wood in the above-ground parts. A characteristic odor can be detected in a cut section of the trunk after the roots have been exposed to gas (66). Following disintegration of the phloem, cortex, and cambium there is a change in the physical properties of the bark, causing it to dry out and crack open, exposing the underlying tissues (66, 73). This may soon be followed by fungal and bacterial invasion. Species of fungi in the genera Polystictus and Schizospyllum have been isolated as well as the bacterium Penicillium. A complicated process of wood decay follows which soon makes the wood unsalvageable even for firewood (75).

Stone (73) makes a final statement concerning the symptoms observed following gas exposure of the roots. He states, "All the conditions refer merely to the way in which a tree succumbs to gas poisoning, and do not necessarily constitute reliable symptoms of this type of injury, as these symptoms may be found in trees dying from other causes. The tissue furnishes the most reliable symptoms for diagnosis."

Stone (73) has carried out a study, to observe the effect of illuminating gas upon vegetation when provided to the above ground parts. He observed that Kenilworth ivy, papyrus, tobacco, tomato and others were damaged, while ferns, mosses and liverwort were hardly affected. He suggests that because the latter group have evolved in time much earlier than the former, that they are tolerant to a wider range of gas exposure. If this holds true, species such as palm and ginkgo tree would be more tolerant to illuminating gas exposure to above ground portions than modern deciduous and conifers, e.g. black cherry, red oak, white spruce, etc.

In the spring and summer of 1934 Deuber (67) carried out an experiment with the purpose of recording the influence of various rates of flow and quantities of a typical manufactured gas on the growth of three-year old American elms (Ulmus americana). These trees were growing in clay pots and were transplanted just before gas exposure to pots containing one liter of soil. Unlike the work described up to this point, this manufactured gas contained no ethylene. Table 2 contains an analysis of the gas used. In addition to the gassed trees, controls were transplanted and handled in a similar manner.

TABLE 2. ANALYSIS OF COKE OVEN GAS SUPPLIED BY NEW HAVEN GASLIGHT COMPANY

Substances	% Composition by Volume
Carbon Dioxide (CO_2)	1.70
Illuminants	3.00
Oxygen (O_2)	0.20
Carbon Monoxide (CO)	8.70
Hydrogen (H_2)	51.00

(continued)

TABLE 2. (continued)

Substances	% Composition by Volume
Methane (CH_4)	25.90
Nitrogen (N_2)	10.0
Naphthalene ($C_{10}H_8$)	3.5
Sulphur (S)	trace
Hydrocyanic Acid (HCN)	--

NOTE: Obtained from reference #67.

He exposed ten elm trees to various gas flow rates and various quantities of total gas supplied. The earliest symptoms observed were chlorosis of the leaves and defoliation. Chlorosis generally involved the leaf margins first and sometimes proceeded no further. Usually the lower-most leaves on the main stem or larger branches became chlorotic and abscised before the younger upper leaves. This is in direct conflict to the pattern seen when trees were gassed with illuminating gas containing ethylene (74). The trees receiving the highest quantities of gas in the shortest period of time became defoliated within five days. However, both trees produced an enormous amount of new shoots within a month. The condition of these new shoots was unreported at this time. The trees supplied with lesser amounts of gas gave a variety of responses ranging from gradual defoliation over a three month period to slight chlorosis. The tree in soil through which 7 cu. ft. of gas had been passed continued to be normal in appearance except for a slight chlorosis at the bases of three leaves. The following spring, these trees exhibited normal growth of tops and roots. Deuber (67) has discussed in this same paper his personal observation of trees apparently injured by root exposure to illuminating gas leaks. He states, "Rapid killing of a shade tree within a few days or a few weeks has been seen occasionally, but the more numerous cases are those in which chlorosis of the foliage or a portion of the tree and partial defoliation is subsequently followed by the drying out and death of uppermost twigs, and the drying of some branches and not others."

Other experiments carried out by Deuber in which woody plants were subjected to a "mixed illuminating" gas and, in some instances, to ethylene, led him to describe three classes of plant physiological responses to this illuminating gas. The first response is stimulation, such as accelerated development of latent buds and proliferation of root parenchyma. The second class of responses is injury, such as inhibition of bud development and dwarfing of leaves. The third response is killing effects, ranging from partial to complete defoliation. The type and degree of the physiological response of small elm trees varied with time of exposure (season) and with the part of the plant exposed to the gas i.e. roots or leaves.

Deuber (67) worked with ethylene in concentrations of 1% to 5% in air held about the bases of rooted cuttings of privet or small oak trees and observed chlorosis, defoliation, and drying out of the leaves on the top of the plants. He has concluded from this and his above experiment with illuminating gas that "ethylene or gaseous ingredients of similar physiological action on plants can explain the symptoms observed when relatively large volumes of the coke oven gas employed in this investigation are passed into the soil in which small elm trees are growing".

SUMMARY

The deleterious effects of illuminating gas on many species of plants have been observed, demonstrated, and reported frequently since the early nineteen hundreds. A few species have also been reported to be relatively tolerant to the presence of illuminating gas in their root zone. Tables 3 and 4 list these tolerant and sensitive species as reported in the literature.

TABLE 3. PLANT SPECIES RELATIVELY TOLERANT TO ILLUMINATING GAS AS REPORTED IN THE LITERATURE

Common Name	Genus-Species
Birch (71)	Betula
American Linden (71)	Tilia americana
Rough Fruited Maple (71)	Acer sp.
Norway Maple (76)	Acer platenoides
Privet (67)	Ligustrum
Mosses (70)	
Ferns (70)	
Liverworts (70)	
Locust seedlings (74)	Gleditsia sp

TABLE 4. PLANT SPECIES RELATIVELY SENSITIVE TO ILLUMINATING GAS AS REPORTED IN THE LITERATURE

Common Name	Genus-Species
Sycamore (71)	*Platanus*
Silver poplar (71)	*Populus*
American Walnut (71)	*Juglans sp*
Tree of Heaven (71)	*Ailanthus altissima*
American Elm (70, 71)	*Ulmus americana*
Dracaena (71)	*Dracaena*
Horsechestnut (71)	*Aesculus hippocastanum*
Alder (70)	*Alnus*
Apple (70)	*Malus*
Ash (70)	*Fraxinus*
Boxelder (70)	*Acer negunda*
Catalpa (70, 67)	*Catalpa bignonioides*
American Linden (70, 67)	*Tilia americana*
Pear (70)	*Pyrus*
Poplar (70)	*Populus*
Euonymous (71)	*Euonymous europea*
Willow (67)	*Salix*
Cherry (67)	*Prunus*
Silver Bell (67)	*Halisia caroliniana*
Red Oak (67)	*Quercus rubra*
Black Oak (67)	*Quercus velutina*
Bermuda grass (74)	*Cyndon dactylon*
Fuchsia (71)	*Fuchsia*
Salvia (71)	*Salvia splendens*

In most of the studies where gas was injected into the root zone the leaves dried. Trees growing in the vicinity of illuminating gas line leaks have exhibited similar symptoms as well as bark-peeling and tissue-staining. Ethylene has been demonstrated to be one of the prime factors involved in the toxic effect of illuminating gas on vegetation in very minute quantities.

Effect of Carbon Dioxide on Plant Growth

Since carbon dioxide can be produced in the refuse and in the soil saturated with methane an investigation into what effects this could have on plant growth is in order.

In our field survey concentrations of carbon dioxide in the soil ranged from less than 1% to 34% of the soil atmosphere. A large percentage of these readings were in the 5% to 15% range (77). Normal soil carbon dioxide usually ranges from 0.04% to 2% (17); therefore, the levels recorded in the survey are excessive.

In 1914 H. A. Noyes saturated the soil around tomatoes and corn plants with carbon dioxide. Both species died in two weeks but there was no irreversible damage to the soil (16). Ruben and Kama in 1940 demonstrated the uptake and fixation of carbon dioxide by barley roots. They used a radioisotope tracer to show this but were unable to isolate the products of fixation in the plant (78). This was done in 1953 by Poel who identified the products of fixation as citric, aspartic and glutamic acids, serine, asparagine, glutamine, tryosine and alpha-keto-glutaric acid (79). Stolwijk and Thimann in 1957 found that the products of carbon dioxide fixation in the roots of pea seedlings were transported to the shoots. They also found that concentrations of 0.5% carbon dioxide stimulated root growth but 1% carbon dioxide inhibited root growth (80). Geisler found that exposing pea seedlings to 5 to 250 milligrams of CO_2 per liter in a hydroponic solution stimulated root growth (81). The stimulation noted was in root elongation; the roots were thinner and an increase in the rate of lateral root initiation was also noted. This stimulatory effect of low levels of carbon dioxide were attributed to the ability of the roots to use it as a carbon source. In light of more recent developments it seems more likely that the carbon dioxide is competing with ethylene for a receptor site. This competition results in a more pronounced auxin response. Increased cell elongation would be characteristic of this hormonal imbalance (82).

There has been a lot of work done on establishing tolerance in various species to excess carbon dioxide in the root zone. A good deal of variation in tolerance between species has been found. Cotton seedlings grown in hydroponic solutions were able to exhibit optimum growth with 10% carbon dioxide present, provided at least 7.5% oxygen was also present. Thirty to forty-five percent carbon dioxide was found to severely reduce root growth (17). Red and black raspberries were killed when their roots were exposed to 10% carbon dioxide. The root growth in the species, Pisum sativum, Vicia faba and Phasedus vulgaris, was completely inhibited by 5.5% carbon dioxide (18).

The ability of carbon dioxide to disrupt the normal function of root cells was investigated by Norris, Weigand and Johanson in 1959. Excised onion root tips were exposed to an atmosphere of 90% oxygen and 10% carbon dioxide. The rate of respiration was halved and when the same tissue was flushed with pure oxygen the rate continued to halve. This was attributed by the authors to be due to permanent damage to the cells caused by dissolved carbon dioxide lowering the pH (19).

Effect of Low Oxygen on Plant Growth

Low concentrations of oxygen have been reported in the soil near natural gas leaks (13). A similar situation has been found both on and adjacent to sanitary landfills. In this study oxygen concentrations in the soil on landfills were found to range from 1% to 20% of the soil atmosphere (77).

In 1945, Chang and Loomis conducted a general survey of the literature and concluded that plants would survive concentrations of oxygen in the root zone of one to two percent. They also concluded that most plants should function normally at oxygen concentrations ranging from five to ten percent (83). There is, of course, a good deal of variability between the different species in their tolerance to low oxygen concentrations in the root zone. Orange tree roots stopped growing when oxygen levels were between 1.2% and 5% and were retarded at concentrations of 5% to 8% at 28°C (84). Apple trees were found to require 10% oxygen for good growth to occur but they could survive concentrations as low as 0.1% (85). Ten percent oxygen was found to inhibit the growth of both red and black raspberries (18).

Higher temperatures were found to increase the need for oxygen in growing roots (18). A dense soil will also increase the need for oxygen at the growing root tip. This is believed to be due to the extra work that has to be done by the root tips as they push their way through the soil (86).

Sustained low oxygen concentrations in the soil have been found to result in mineral deficiency symptoms in the plant. Potassium is usually the first to occur and it is followed in order of appearance by nitrogen, phosphorus, calcium and magnesium (87, 88).

EFFECTS OF LANDFILL GASES ON SOIL QUALITY

In investigations of the effects of natural gas (methane) leaks on physical properties of soils, several investigators (89, 13, 90, 15, 91) reported increases in pH, organic matter, available phosphorus, calcium, potassium, iron, manganese, nitrate-nitrogen, ammonia-nitrogen, and moisture content in areas around the gas leaks as compared with normal soil away from the leaks. In some cases the fertility of the soil was increased by leaking gas to the point that crops such as wheat and oats grew better on the gassed soils than on normal soils (90). The fact that the ratio of organic matter to nitrogen was generally lower in the gassed soil led to the conclusion that the soil alterations were probably due to the activity of micro-organisms under anaerobic conditions.

The reason for the observed increases in concentrations of nitrogen compounds and trace elements in gassed soils undoubtedly lies in the low redox potential of these soils, as has been documented for similar responses of soil to flooding conditions (92, 93, 94). When oxygen disappears from the soil, requirements of anaerobic soil microorganisms for a source of oxygen results in the reduction of several oxidized compounds namely nitrate, nitrite, and the higher oxides of manganese, and iron. These reduced forms are generally more soluble and hence are made available to plants. Availability of other trace metals occurs as they are displaced by ferrous ions from the exchange complex to the soil solution.

The trend to neutrality in pH is probably caused by the buffering effect of organic acids released by the microbial breakdown of organic matter.

The consequences of these soil changes in landfills have yet to be evaluated. At this time it is considered that these soil conditions contribute to the damage done to vegetation, although to a lesser degree than does the presence of landfill gas. However, the presence of ammonia-nitrogen or of trace elements in toxic concentrations might hasten the death of vegetation already debilitated by the presence of toxic gases and/or the lack of oxygen in the root atmosphere.

SECTION V

NATIONAL SURVEY OF PROBLEM

MAIL SURVEY OF VEGETATION PROBLEMS ASSOCIATED WITH REFUSE LANDFILLS

Procedure

The investigation to determine the geographic extent of problems associated with growing vegetation on completed landfills was conducted in two stages, the first of which was a mail survey for the purpose of obtaining preliminary information on the location of and the vegetative condition of former sanitary landfills which have been converted to parks, playgrounds, golf courses or other types of recreational areas.

On the basis of information obtained through the mail survey, specific landfills were selected for site visits, so that the nine climatological regions of the United States and territories (Figure 1) proposed by Trewartha in his textbook entitled An Introduction to Climate were covered.

Approximately 1,000 letters were sent to people and publications throughout the United States explaining that we were undertaking a survey to determine the extent of problems associated with growing vegetation adjacent to, and on top of completed solid waste refuse landfills.

Appendix A is a copy of the basic letter sent to most of these people. A total of seven differently worded letters was sent. However, a majority of the people receiving the letters of inquiry received the basic letter. Most of the other six letters contained only slight modifications of the letter in Appendix A. The modifications were made to accommodate the different audiences. The letter in Appendix A was reproduced by the Itek system. The address and salutation for each letter recipient were individually typed and each closing signature was individually written In cases where the letter sender, Franklin B. Flower, personally knew the recipients of the letter, an additional personal postscript was added to the letter to encourage their response.

A questionnaire (Appendix B) and a stamped, self-addressed envelope were enclosed with each letter. The questionnaire requested the names and addresses of landfills which have had problems growing vegetation above them or adjacent to them and the names and addresses of landfills which have been successful in growing grass, shrubs, trees or other vegetation. Comments on the effects of buried refuse on living surface vegetation were also sought. The enclosed self addressed, stamped envelope enabled the recipient to easily return the questionnaire. The questionnaire was designed so that it would

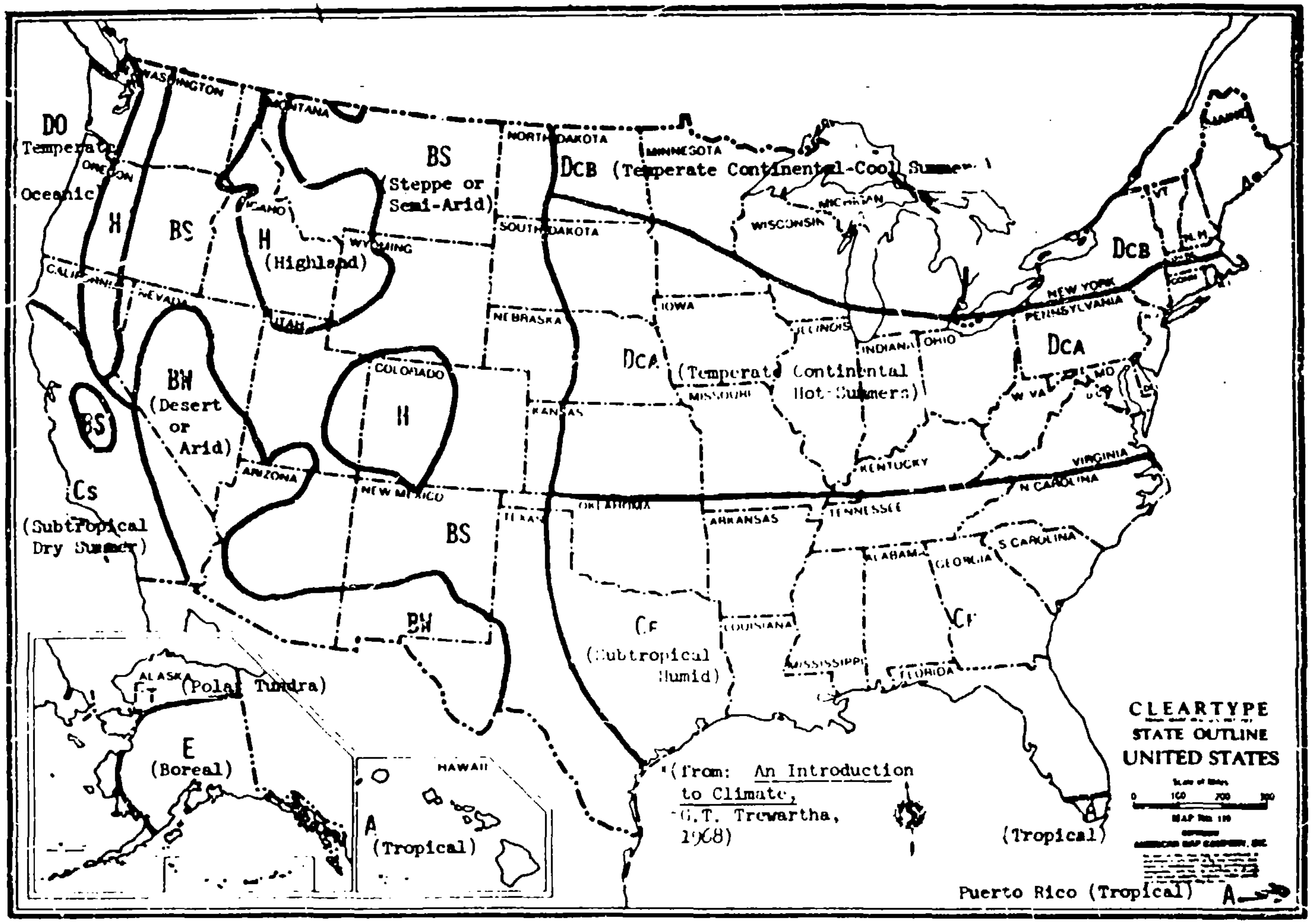


Figure 1. Major United States climate types*

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take a minimum amount of effort to complete but would supply information which would enable us to locate those refuse landfills which showed the best and poorest vegetation growth associated with them. We included a notation that could be check-marked to indicate that the person completing the questionnaire would like to obtain a summary report of the results of the completed study. It was felt that this would encourage the recipient to complete and return the questionnaire.

Appendix C lists the sources from which we obtained the addresses of the recipients of the questionnaires and the number of questionnaires sent to each of these groups. The State Soil Conservation Service Office, the Director of the Cooperative Extension Service, and the Solid Waste Management Office in every state and territory received this written request for information. The thirty-three publications with which we communicated were the major publications of the solid waste management field. Mailing of the questionnaires to people on the various registration and membership lists was done on a selective basis. The 130 mailings listed under "other" included consultants; landfill operators; directors of county, city and municipal solid waste management programs; educators; etc. The names and addresses of many of these "other" people were obtained from the replies received from earlier mailings.

The State Soil Conservation offices in Alabama, Iowa, and Texas made copies of our letter and questionnaire which they forwarded to their regional (county) offices. After assembling the data, they returned to us either the individual replies or a compilation of the replies. At the request of the individual State Soil Conservation Service offices, we sent questionnaires to each regional office in New Jersey and to twelve of New York State's regional offices.

Results

Approximately 500 replies were received from the survey in addition to the 40 returned by the Post Office as undeliverable. Of these, 115 indicated they had no knowledge of the situation. The balance of the replies contained information on approximately 500 refuse landfill sites.

The results are summarized in Table 5 according to the major climatic zones as outlined in Figure 1, which follows the climate types presented in An Introduction to Climate by Glen T. Trewartha, 4th edition, 1968.

Adding the number of sites reported in Table 5 with no problems growing vegetation to those reporting growing problems on and/or adjacent to the landfill gives a total of 544, or 37 more than the total number of sites reported. This apparent inconsistency is due to two or more conditions being reported to exist concurrently at some landfills.

The mail survey results indicate that of the sites reporting:

76% were growing vegetation without problems;

25% had problems growing vegetation on the soil cover;

7% were experiencing difficulty in growing vegetation adjacent to the landfill;

17% were successfully growing trees on the landfill;

63% grew grass successfully on the landfill;

12% grew shrubs successfully on the landfill.

No significant difference was noted in the degree of problems reported from landfills located in the different meterological zones (Table 6). Sixteen or more reports were received from each of the five climatic zones. Of these, the percent of sites reporting no growing problems ranged from 72% to 77% and the percent reporting some kind of vegetative growth problem varied from 30% to 48% of the total number of sites reporting. Table 7 summarizes the results by states.

Thirty-eight replies commented on the possible causes of vegetation growth problems on refuse landfills and what should be done about them. The most frequently reported suggestions and the percent of people reporting each suggestion were:

47% - Use or develop a good quality soil and good cultivation practices;

32% - Landfill gases inhibit vegetation growth;

32% - Use more than two feet of cover for good vegetation growth;

26% - Grow grass or other shallow-rooted crop;

13% - Vent or block landfill gases to keep them away from the root zone of vegetation;

11% - Consider adaptable species;

11% - Leachate causes vegetation growth problems;

11% - Well-compacted refuse will enhance vegetation growth;

11% - Good surface drainage enhances vegetation growth.

While the major reason reported for poor vegetation growth was the lack of good soil and/or poor cultivation practices, a high percentage of those reporting did give the presence of landfill gases as a major cause of this poor growth. Others suggested various methods for keeping the gases away from the root zone of vegetation as an aid to better growth.

Although we have been able to produce very nice tables from the data obtained from the mail survey, the degree of accuracy of this data is suspect. In the section of this report which gives the results of the field visits

TABLE 5. LANDFILL VEGETATION GROWTH RESULTS BY CLIMATIC ZONE AS REPORTED IN MAIL SURVEY

Major Climate Zone		Total Number With No Problems	Growing				Vegetation Growing Problem		Total # Sites Reported
Symbol	Name		Grass	Shrubs	Trees	Other	Adjacent to Landfill	On Covered Landfill	
Cf	Subtropical Humid	83	70	8	24	10	-	32	112
Dcb	Temperate Continental Cool Summers	25	16	2	5	2	2	8	33
Dca	Temperate Continental Hot Summers	223	192	36	41	22	24	63	291
BS	Steepe or Semi-Arid	13	8	--	1	1	2	6	18
Cs	Subtropical Dry Summer	18	13	12	12	--	2	10	25
Bw	Desert or Arid	2	1	--	--	--	--	--	2
Do	Temperate Oceanic	8	7	--	3	--	--	2	9
H	Highland	6	6	--	--	--	--	1	6
Aw	Tropical Wet and Dry	--	--	--	--	--	--	--	0
Ar	Tropical Wet	--	--	--	--	--	--	1	1
A	Tropical (Hawaii)	6	6	4	2	--	--	4	10
	TOTAL	384	319	62	88	35	33	127	507

TABLE 6. COMPARISON OF VEGETATION GROWTH PROBLEMS BY CLIMATIC ZONES

Major Climate Zone Symbol	Major Climate Zone Name	Number Stations Reporting	Percent - No Growing Problems	Percent - Problems Growing Veg. on Landfill	Percent - Problems Growing Veg. Adjacent to Landfill
Cf	Subtropical Humid	112	74	29	3
Dcb	Temperate Continental Cool Summers	33	76	24	6
Dca	Temperate Continental Hot Summers	291	77	22	8
BS	Steppe or Semi-Arid	18	72	33	11
Ca	Subtropical Dry Summer	25	72	40	8

TABLE 7. RESULTS OF MAIL SURVEY BY STATES AND TERRITORIES

	No. Problems	Problem Adj.	Problems On	Total No. Sites Reporting
Alabama	17	0	14	31
Alaska	0	0	0	No Ld.Fls. Reptd.
Arizona	6	2	2	9
Arkansas	7	2	5	12
California	20	2	11	28
Colorado	0	0	0	No Ld.Fls. Reptd.
Connecticut	8	1	2	10
Delaware	11	2	0	11
District of Col.	3	0	1	3
Florida	7	0	1	8
Georgia	1	0	0	1
Hawaii	6	0	4	10
Idaho	5	0	0	5
Illinois	5	0	2	7
Indiana	12	0	0	12
Iowa	46	0	5	51 (might be some overlap)
Kansas	0	0	0	0
Kentucky	9	0	0	9
Louisiana	1	0	0	1
Maine	0	0	0	No Ld.Fls. Reptd.
Maryland	16	2	4	20

(continued)

TABLE 7. (continued)

	No. Problems	Problem Adj.	Problems On	Total No. Sites Reporting
Massachusetts	7	1	3	11
Michigan	7	2	0	9
Minnesota	4	0	1	5
Mississippi	0	0	6	6
Missouri	2	0	0	2
Montana	3	0	2	3
Nebraska	1	0	0	1
Nevada	0	0	0	No Ld.Fls. Reptd.
New Hampshire	4	0	1	5
New Jersey	30	8	11	45
New Mexico	2	0	1	3
New York	27	3	15	41
North Carolina	12	0	1	13
North Dakota	5	0	0	5
Ohio	12	2	11	22
Oklahoma	5	0	2	5
Oregon	8	0	1	8
Pennsylvania	11	0	5	16
Puerto Rico	0	0	1	1
Rhode Island	2	3	2	7
South Carolina	13	1	1	15
South Dakota	0	0	0	0

(continued)

TABLE 7. (continued)

	No. Problems	Problem Adj.	Problems On	Total No. Sites Reporting
Tennessee	4	0	0	4
Texas	19	0	3	19
Utah	2	0	1	2
Vermont	2	0	0	2
Virginia	13	1	6	19
Washington	1	0	1	2
West Virginia	2	1	0	2
Wisconsin	6	0	1	6
Wyoming	0	0	0	No Ld.Fls. Reptd.
GRAND TOTAL	384	33	127	507

NOTE: Some landfills are listed in more than one category and examinations, we have compared the information received by mail and what was found in the field. This comparison indicates that one-third of the reports received by mail may have been inaccurate.

SITE SURVEY OF VEGETATION PROBLEMS ASSOCIATED WITH REFUSE LANDFILLS

Introduction

From the completed questionnaires received in response to the mail survey, landfill sites were selected which showed the best and the poorest vegetation growth associated with refuse landfills in the following nine climatic areas (Figure 1):

(1) Ar - Tropical wet.
(2) BS - Steppe or semi-arid.
(3) Bw - Desert or arid.
(4) Cf - Subtropical humid
(5) Cs - Subtropical dry summer.
(6) Dca - Temperate continental-warm summers.
(7) Dcb - Temperate continental-cool summers.
(8) Do - Temperate oceanic.
(9) H - Highland.

Procedures

Before planning the site visits, an inventory was made of all the equipment required for making the landfill vegetation and soil studies (Appendix D).

The following field procedure was designed to insure the maximum possible data from each landfill site visited. Field data were recorded on field inspection report forms (Appendices E and F).

1. After arriving at the site, preferably one involving the growth of trees and/or agricultural crops, with field equipment (Appendix D) communicate with the official contacts and make friends.

a. Obtain a history of the site and the vegetation growth from the local officials. Find out what materials went into the landfill, how well they were compacted, how deep is the refuse, when it was put in the landfill; thickness and type of daily, intermediate and final cover, etc. Find out when vegetation was planted and how well it is growing.

b. Record names, addresses, and telephone numbers of all contact persons. Record physical and mailing addresses of the site.

2. Make or obtain a rough map of the site noting areas of poor and good vegetation growth.

3. Establish reference points to and from which compass bearings can be taken and distance measurements can be made so that an accurate map can be made and the good and poor vegetation growth areas can be located accurately

in relation to the completed fill. This map should include the location of the completed landfill, vegetation, buildings, and where pictures were taken.

4. Take distance measurements and compass directions to reference points from the centers of the poor vegetation growth areas or from a specific location within the poor vegetation growth area.

5. When the poor vegetation growth areas are located, place or locate a reference marker in this area. Locate it at the center of the poor growth or at the spot previously located in number 4. All sampling points in the poor vegetation growth area should be taken in relation to the reference marker.

6. Repeat number 4 and number 5 for a comparable good vegetation growth area where the same species of crop is being grown as in the poor growth area.

7. Starting at the reference marker and moving out in as many directions as possible, take combustible gas readings at the 3' depth in the poor and good vegetation growth areas. The spacing and number of the sampling points will be determined by the size of the poor growth area and the amount of time available.

8. At intermediate sampling points in both areas take combustible gas samples at 1', 2', and 3' depths. Sample for O_2 and CO_2 at the 1' depth. Where possible, intermediate sampling sites should be located in the vicinity of sampling sites that were previously found to contain high concentrations of combustible gas at the 3' depth.

9. Take soil samples according to soil sampling procedure (Appendix G).

10. Identify species of the good and poor growth vegetation and the possible causes of poor growth.

11. Photograph the site including good and bad vegetation sampling locations. Record locations of photographs. Include vistas and close-ups of individual plants and/or leaves showing injury.

12. Sample and analyze any visible leachate which is in a vegetation growing area. Follow leachate sampling and analysis procedures (Appendix H).

13. Give contact people a general oral presentation of your observations and test results. If they request it, send them a copy of the report at a later date.

14. Record the following temperatures and their locations.

a. On landfill

1. Soil at 3' depth in area of poor vegetation growth and a high concentration of landfill decomposition gases.

2. Soil at 3' depth in area of good vegetation growth.

b. Off landfill

1. At 3' depth in an area not influenced by landfill.

2. Soil at 3' depth in area of poor vegetation growth.

c. Ambient air in the shade.

15. Determine depth of cover over landfill refuse in areas of poor and good vegetation cover.

16. Note: Report data on "Landfill Vegetation Field Inspection Form" (Appendix E) and "Gas Sample Analysis Form" (Appendix F).

Evaluation of Landfills Surveyed

Introduction

During 1975, 1976, and 1977 over fifty landfills and former landfills were visited throughout the United States and Puerto Rico (Figure 2) for the purpose of evaluating the quality of vegetation growth on or adjacent to the former landfill.

The sites visited were chosen from the replies received from the mail survey supplemented by information obtained via telephone conversations. A half-dozen additional "landfills" were visited, but for various reasons they are not included in this report - in some cases they turned out not to be true refuse landfills and sometimes we were not able to obtain enough information to present reliable data.

The reports on the field trips are grouped by major climatic zones. These are arranged in alphabetical order according to their letter symbols. The detailed data are contained in Appendix I.

Landfills Surveyed According to Meteorological Regions

Ar - Tropical wet climate (Puerto Rico, 3/21-24/77)--The following three sanitary landfills were investigated in Puerto Rico between March 21 and March 24, 1977:

3/22/77 - San Juan Sanitary Landfill
Route #1, 7 miles south of San Juan.

3/23/77 - Bayamon Sanitary Landfill
Barrio Buena Vista, $4\frac{1}{2}$ miles SSE Bayamon along
Route #167.

3/23/77 - Cayey Sanitary Landfill
3 miles east of Cayey off Route #1.

All of these landfills receive municipal and light industrial refuse. Bayamon was closed in 1974 by a court order whereas San Juan and Cayey are still operating. No attempts to vegetate any of these landfills was under-

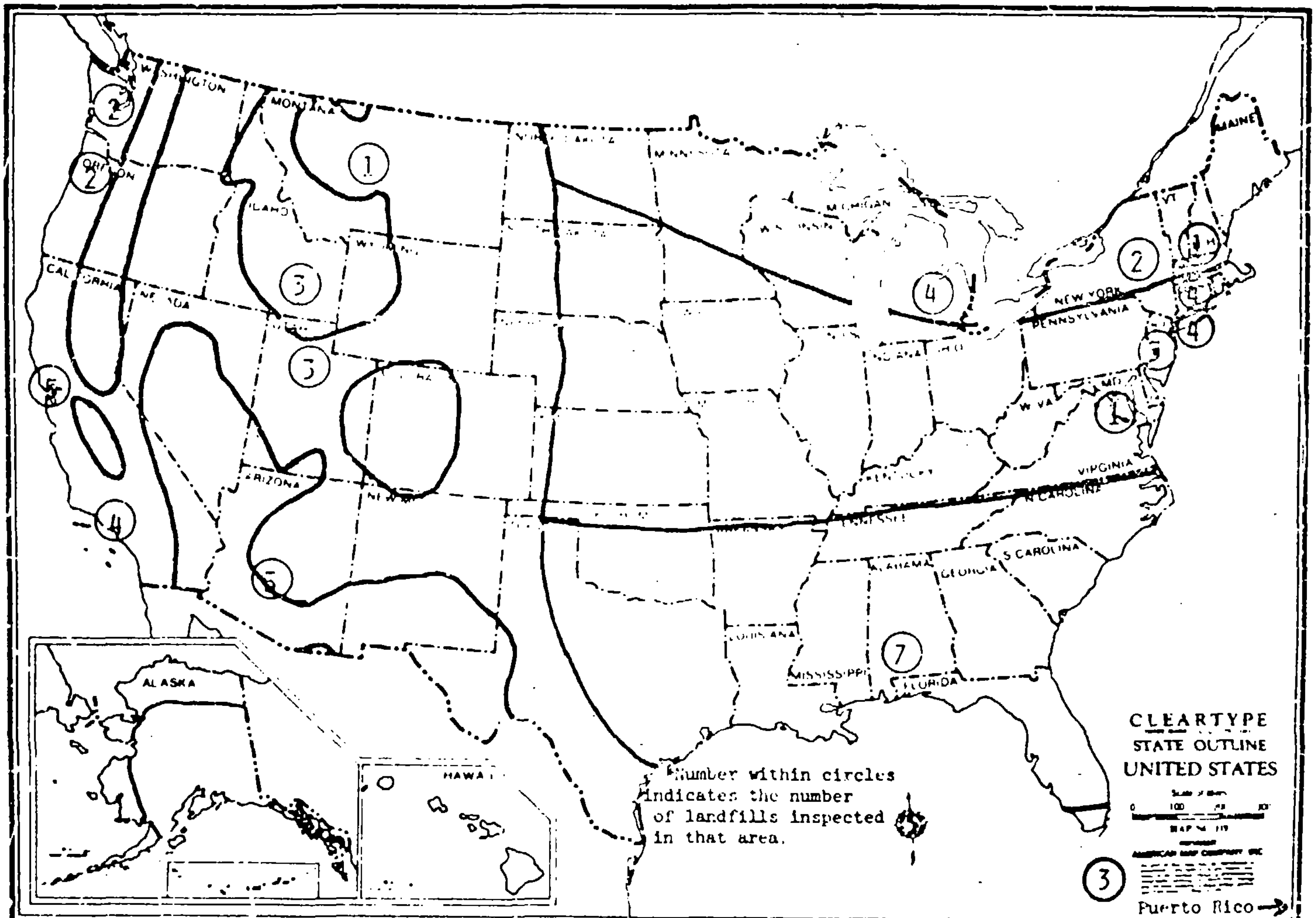

Figure 2. Location of landfills evaluated for quality of vegetation growth*

taken; however, volunteer plants were scattered about the surface of San Juan and Bayamon.

On the San Juan landfill combustible gas was found to be higher in the areas where vegetation died than in areas which supported healthy vegetation. The root zone beneath a severely defoliated legume tree adjacent to Bayamon landfill contained higher combustible gas concentrations than a nearby healthy tree. No vegetation was growing on the Cayey landfill, and there were no signs of lateral gas migration.

In summary, combustible gas concentrations in the soil atmospheres related positively to dead and unhealthy vegetation.

BS - Steppe or semiarid climate (Utah and Montana, 8/30-9/3/76)--Four former landfills were examined in northern Utah and western Montana:

8/30/76 - Pioneer-Cannon Stakes Dairy, Salt Lake City, UT.

8/31/76 - Timpanogos Golf Course, Provo, UT.

8/31/76 - South Street Sanitary Landfill, Provo, UT.

9/03/76 - Great Falls Sanitary Landfill, Great Falls, MT.

All of these sites were planted with vegetation. However, only a minor part of Timpanogos Golf Course was constructed over a former landfill, and the Russian olive trees planted at the South Street Sanitary Landfill were actually adjacent to the former landfill. Correlations between high combustible gas and poor vegetation quality were noted at Great Falls and to a lesser extent at Pioneer-Cannon Stakes Dairy. The row of olive trees at the South Street Sanitary Landfill were planted on a berm, adjacent to the landfill, to which no combustible gas had migrated.

BW - Desert or arid climate (Phoenix-Glendale, Arizona, 1/17-1/20/77)--Five former landfills were examined in the Phoenix and Glendale region of Arizona:

1/18/77 - Del-Rio Sanitary Landfill, 7th St., Phoenix (A)

1/18/77 - Deer Valley Park, 19th Ave., Phoenix (B)

1/19/77 - Johnson's Farm, Olive Avenue & 98th Avenue, Maricopa Co. (C)

1/19/77 - Glendale Nursing Home, Olive and 107th Avenues, Maricopa Co. (D)

1/20/77 - Sutton's Farm, Northern Ave. and 103rd Ave., Maricopa Co. (E)

Combustible gas concentrations were generally low in the soil covering the refuse of these five landfills. No relation between combustible gas concentrations and vegetation quality were found at sites A, B and D and a very small negative relation (the more gas the poorer the vegetation) were found at sites C and E. The major problems with growing vegetation on these five sites appear to be a combination of rocky soil, lack of water, surface settlement, and transplanting difficulties.

Soil temperatures did not appear to be correlated with the viability of vegetation on any of the sites.

Cf - Subtropical humid climate (Southern Alabama, 8/15-24/76)--Seven former landfills were examined in the southern portion of Alabama:

8/16/76 - Montgomery #2 Wareferry Road, East Montgomery.

8/17/76 - Selma Sanitary Landfill, Route 80, Selma.

8/17/76 - Montgomery #1 Sanitary Landfill, Montgomery.

8/18/76 - Gautier St. Landfill, Tuskegee.

8/19/76 - Old Dothan City Landfill, Ashford.

8/20/76 - Atmore Sanitary Landfill, Escambia County.

8/23/76 - Chatom City Landfill, Chatom.

A correlation was found between dead or poorer quality vegetation and presence of combustible gases in the soil sites at Montgomery #1, Gautier St., Old Dothan City, and Atmore. Little combustible gas was found at Montgomery #2 and Selma sites and no combustible gas was found at the Chatom City landfill.

Cs - Subtropical dry climate (San Francisco-Los Angeles, California, 1/76)--In the San Francisco area five sites, all of which were reclaimed from San Francisco Bay by diking, were selected for investigation. The refuse ranged in depth from 15 to 40 feet, and in age from recent to over 80 years. The cover material on these sites tended to be very heavy clay, but it was frequently used very sparingly. As of January 1976, three of these sites (Marine Park, Galbraith, and Alameda) have been converted into golf courses; the remaining two (Mountain View and Oakland Scavenger) will become golf courses when filling is completed. All three golf courses have been developed successfully, but only the Marine Park site has not experienced serious problems with vegetation.

The three golf courses are located on refuse which contains a limited amount of putrescible material. The two landfills still to be converted into golf courses are said to contain much more putrescible refuse. This could result in more extensive problems with settlement and landfill gases than experienced at the other sites. A positive relationship was found between high concentrations of landfill gases and poor growth of cypress and Monterey pine trees at the Oakland Scavenger Company's Davis Street Landfill.

Four former landfills, all constructed by the County of Los Angeles Sanitary District, were examined in the Los Angeles area. They were the South Coast Botanic Garden, South Coast County Park, Mountain Gate Golf Course, and Mission Canyons #1, 2, and 3. All of these landfills have a maximum depth of at least 100 feet. A mixture of municipal and industrial waste was deposited at the South Coast Botanic Garden and South Coast County Park sites which are located in former diatomaceous earth mines. The remaining landfills, which were constructed in canyons, contain primarily municipal refuse. The Los Angeles landfills had considerably more cover material than those in the San Francisco area.

A considerable effort has been put into replanting these landfills by governmental agencies and private concerns. The results were the most successful we observed on our tour of sites throughout the country. All of the sites have had problems due to settlement, landfill gases or high soil temperatures. These problems, however, didn't appear to seriously detract from the overall success of the sites.

At the South Coast Botanical Garden a direct relationship was observed between the poor growth of vegetation and the occurrence of landfill gases in the soil. There was also found a direct relationship between the occurrence of high soil temperatures and poor growth of vegetation. A direct relationship between the occurrence of landfill gases in the soil and the poor growth of vegetation was also observed at the South Coast County Park, Mission Canyon Landfill, and the Mountain Gate Golf Course.

Dca - Temperate continental-warm summer climate (Northeast United States) --During 1975 and 1976 the following 12 landfills were visited in the warm summer temperate continental climatic region:

6/19/75 - Hunter Farm, Cinnaminson, NJ.

6/24/75 - DeEugenio Bros. Peachtree Farm, Glassboro, NJ.

7/31/75 - University of Connecticut at Storrs, Storrs, CT.

8/01/75 - Farmington Sanitary Landfill, Unionville, CT.

8/06/75 - Holyoke Sanitary Landfill #1, Holyoke, MA.

8/06/75 - Holyoke Sanitary Landfill #2, Holyoke, MA.

4/08/76 - Erlton Park, Cherry Hill, NJ.

6/29/76 - Kenilworth Demonstration Landfill Project, Washington, DC.

10/14/76 - Holtsville Sanitary Landfill, Brookhaven, L.I., NY

10/14/76 - Kings Park Sanitary Landfill, Smithtown, L.I., NY.

10/15/76 - Huntington Sanitary Landfill, Huntington, L.I., NY.

10/15/76 - Bethpage Sanitary Landfill, Oyster Bay, L.I., NY.

Eight sites (Hunter Farm, DeEugenio Bros., Farmington, Holyoke #2, Holtsville, Kings Park, Huntington, and Bethpage) have dead trees and/or poor growing vegetation directly associated with the presence of landfill gases in the soil. However, the concentration of landfill gases at Farmington was very low.

At two sites, Kenilworth and Storrs, combustible gas correlated with poor growing vegetation in some instances; however, not all poorly growing vegetation was associated with the presence of combustible gas.

It appeared that poor planting practices and the lack of irrigation were the major contributors to the demise of trees planted on the former landfills at Kenilworth and Erlton Park.

Holyoke #1 was used as landfill for incinerator ash. No combustible gas was detected on or adjacent to this landfill.

Seven of these landfills (Hunter Farm, DeEugenio Bros., Holyoke #2, Holtsville, Kings Park, Huntington, and Bethpage) exhibited the correlation of landfill gases in the soil atmospheres and vegetation death in areas adjacent to the landfill. All seven landfills had been placed in former sand and gravel pits.

Dcb - Temperate continental-cool summer climate (Northeast United States, 8/75)--The following seven landfills were inspected during August, 1975:

8/7/75 - Roussel Park, Nashua, NH.

8/11/75- Guilderland Landfill, Guilderland, NY.

8/12/75- City of Auburn Sanitary Landfill, Auburn, NY.

8/18/75- Southeastern Oakland Incinerator Authority, Oakland Co., MI.

8/19/75- Cereal City Landfill #1, Battle Creek, MI.

8/20/75- Cereal City Landfill #2, Battle Creek, MI.

8/21/75- Kalamazoo Landfill, Oshtemo Twsh, MI.

There appeared to be no definite relation between vegetation injury and landfill gases at the Roussel Park or Kalamazoo Landfills. However, an excellent positive relationship was noted between high concentrations of landfill gases in the soil atmosphere and dead or dying vegetation at the Guilderland, Auburn, Oakland and Cereal City landfills. At the Oakland and Cereal City landfills the major vegetation death problems were associated with landfill gases migrating from the landfill beneath the ground. The following vegetation was apparently injured or killed by landfill gases:

Guilderland - volunteer aspen, sumac, and weeds

Auburn - willow trees

Oakland - lombardy poplar and black oak trees, weeds and grass

Cereal City #1 - red pine trees, weeds and grass

Cereal City #2 - white spruce, douglas fir, white fir, and shagbark hickory trees

Do - Temperate oceanic climate (Washington and Oregon, 6-7/76)--Two former landfills were examined in Seattle, Washington: East Campus of the University of Washington and Genesee Street Park. In Oregon two former landfills were evaluated: Day Island in Eugene, and Fowler's Farm in West Salem.

An excellent direct relationship was found between dead vegetation and/or barren ground and the presence of combustible gases in the soil atmosphere and anaerobic soil conditions at the two Seattle sites and at Day Island. The death of trees adjacent to Day Island was correlated positively with the underground migration of landfill gases from the landfill. High soil temperatures were also found to be associated with landfill gases at Day Island.

The wheat field at Fowler's Farm was growing over a former demolition landfill which produced only traces of combustible gas. Where the soil had not settled the wheat growing over the demolition material appeared to grow as well as that growing on nearby virgin ground.

H - Highlands climate (Idaho Falls, Idaho, 8/30-9/6/76)--The three former landfills which were visited in the Highlands climate region were:

9/2/76 - Fremont Park.

9/2/76 - Red Baron alfalfa field.

9/3/76 - Idaho Falls Child Development Center.

A good positive relationship was found between high combustible gas and poor quality vegetation at the Red Baron alfalfa field site, but at the other two sites very little landfill gas was found in the vegetation root zones. Therefore, no direct relationship was observed between the poor vegetation growth and the occurrence of landfill gas pollution in the soil atmosphere at these two sites.

Effects of Landfill Gases on Soil Quality

Top and subsoil samples from each of the nine climatic regions were analyzed for content of major and trace nutrients, pH, moisture, organic matter, conductivity and for soil texture. Data for landfills within each region were averaged (Appendix J, Tables 1-9) and analyzed statistically by Student's "t" test, where data were sufficient. Table J-10 contains a summary of all the topsoil data expressed as percent change (+ or -) in each constituent as the soil proceeded from a non-gas to a plus-gas condition.

The initial content of nutrient elements, as well as the pH of soils, in different landfills and among climatic areas varied widely. However, there was little difference in content of major nutrient elements (magnesium, phosphorus, potassium, and calcium) between gassed and ungassed soil. Since these elements are normally present in soil in hundreds or thousands of pounds per acre, a small percentage fluctuation in content would have a negligible effect on plant growth.

Nitrogen compounds (NO_3-N and NH_4-N) and trace elements (iron, manganese, zinc, copper, and boron) which are normally present in much lesser quantity, increased many fold in soil with high concentrations of gas in their atmospheres. In particular, the ratio of iron to manganese, a critical value in soil fertility, was frequently above the recommended range for adequate plant growth.

Conductivity which is a measure of total ion activity was. understandably, increased as well.

Soil pH was either increased or decreased, depending on the original condition of the soil; the pH of highly alkaline soils, such as those in Utah (steppe) and Idaho (highlands), decreased, while the more acid soils of the Northeast and Northwest increased in pH value.

Comparison Between Field Observations and Mail Survey Reports of Landfill Vegetation Conditions

Approximately 60 refuse landfills were visited during the 1975-77 field survey of landfill vegetation conditions. Thirty-seven of these had been reported through the mail survey prior to the field inspection. A comparison of what was reported by mail and what was found in the field indicated that about 23 (62%) of the responses were correct and about 14 (38%) were inaccurate.

The apparent conflict between what was reported by mail and what was found in the field for more than one-third of the reports was possibly due, in part, to errors in interpretation of the information supplied and to having many of the mail survey questionnaires completed by people who had not personally examined the landfill sites to determine the condition of the vegetation.

Table 8 presents the vegetative growth information reported by mail and the field observations from the same sites. The apparent accuracy of the mail survey report is given for each site. It was sometimes difficult to evaluate the accuracy of the mail report as simply either good or poor, since in a number of cases field examination indicated that part of the report was found to be correct and part incorrect.

TABLE 8. COMPARISON BETWEEN FIELD OBSERVATIONS OF LANDFILL VEGETATION CONDITIONS AND REPLIES TO THE MAIL SURVEY OF VEGETATION CONDITIONS

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Mail Statement
Ar	San Juan Landfill San Juan, Puerto Rico	Problems on the landfill	Problems on landfill	Good
Bsh-Bw	Deer Valley Park Maricopa County Arizona	Problems on landfill	Grass doing poorly Cause not known	Good
Bsh-Bw	7th Street Landfill Phoenix, Arizona	Problems adjacent to landfill	Dead trees near adjacent homes observed	Good
Bsh-Bw	103rd Ave. Landfill Maricopa County Arizona	No problems	Had been farmland Farming was abandoned due to settlement and gas	Poor
Bsh-Bw	Olive Ave Landfill Maricopa County Arizona	No problems grass on landfill	Landfill converted to a nursing home, grass and trees doing well	Good
Bsk	Great Falls S.L.F. Great Falls, Montana	No problems on landfill	Wheat crop on landfill failed	Poor
Bsk	Pioneer-Cannon Stakes Dairy Salt Lake City, Utah	No problems with grass, trees and shrubs	Vegetation doing very poorly on this site	Poor
Cf	Montgomery City Landfill Montgomery, Alabama	No problems growing grass, trees and shrubs	Nothing planted only volunteer vegetation on site, mostly weeds	Poor

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Mail Statement
Cf	Tuskegee Landfill Tuskegee, Alabama	No problems growing grass, trees and shrubs	Nothing growing on landfill at all	Poor
Cf	Dallas Co. Landfill Selma, Alabama	No problems growing grass, trees, or shrubs	Trees and volunteer vegetation doing very well	Good
Cf	Escanbia Co. Landfill Alabama	No problems growing trees	Trees (Pines) doing well, many were chloro-tic, some erosion	Good
Cf	Old Dothan City Landfill Dothan, Alabama	No problems, grass and trees on landfill	Nothing observed planted on landfill, some trees adjacent declining gas suspected	Poor
Cf	Chatom City Landfill Chatom, Alabama	No problems growing trees on landfill	Trees doing well (seedlings)	Good
Cs	South Coast Botanical Gardens, Palos Verdes Los Angeles, California	No problems with grass, trees, and shrubs, problems adjacent	Good sucess on landfill But some problem areas were observed	Poor
Cs	Mission Canyon Los Angeles, California	Problems on landfill	Grass doing well, severe settlement problems observed	Good

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Statement
Cs	Galbraith Golf Course Oakland, California	No problems with grass, trees, or shrubs	Problems observed due to thin cover, settlement, and gas	Poor
Cs	Alameda Municipal Golf Course Almadea, California	Problems on landfill	Severe settlement problems observed	Good
Dca	Oxon Cove Landfill Delaware	Grass growing on landfill	Wild vegetation, no planted vegetation	Poor
Dca	TVA, Land Between the Lakes Park Landfill Kentucky	No problems growing grass on landfill	Grass growing on landfill, some erosion problems	Good
Dca	Univ. of Connecticut Experimental Plot Storrs, Connecticut	Problems on landfill	Grass and alfalfa was growing noticably poorer over refuse	Good
Dca	Farmington City Landfill Unionville, Connecticut	Problems adjacent to landfill	Poor growth of volunteer species was observed on landfill, no evidence of problems adjacent	Poor
Dca	Overpeck Creek Hackensack, New Jersey	Problems on landfill	Some problems were observed but in all a successful operation	Good
Dca	Princeton Disposal S.L.F. South Brunswick, New Jersey	Problems adjacent	Leachate, indicating adjacent wood lot, landfill disrupting surface drainage, flooding trees	Good

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Statement
Dca	Earle Landfill Naval Ammunition Depot Colts Neck, New Jersey	No problems growing grass, trees and shrubs	Pines planted-doing well Good cover of wild vegetation	Good
Dca	Cinniminson S.L.F. Cinniminson, New Jersey	Problems with vegetation adjacent to landfill	Corn, sweet potatoes killed on adjacent farm	Good
Dca	Kenilworth Landfill Washington, DC	No problems with grass and shrubs on landfill Some problems with trees	Grass doing well over most of site, many trees transplanted to site were dead	Good
Dca	Holtsville S.L.F. Brookhaven Long Island, New York	Problems on landfill Grass growing on landfill	Trees and grass not doing very well on landfill. Trees killed adjacent to landfill	Good
Dca	City of Madison S.L.F. Madison, Wisconsin	1) No problems with grass on landfill 2) Problems with grass on landfill	Grass generally doing well on landfill but areas did exist which wouldn't support grass	Good
Dca	Jackson City S.L.F. Jackson, Ohio	No problems with grass, shrubs and trees on landfill	Landfill largely unvegetated	Poor
Dcb	South-East Oakland Incinerator Co. S.L.F. Detroit, Michigan	Problems adjacent to landfill	Poplar trees and wild sumac killed adjacent to landfill	Good
Dcb	Cereal City S.L.F. Battle Creek, Michigan	Problems adjacent to landfill	Trees killed on two sides of landfill	Good

(continued)

TABLE 8. (continued)

Climate *	Site	Reported by Mail	Observed in Field	Accuracy of Statement
Dcb	Holyoke, S.L.F. Holyoke, Massachusetts	Problems with vegetation on landfill	Not much vegetation on landfill. Some dead trees observed	Good
Dcb	City of Auburn S.L.F. Auburn, New York	No problems with grass and shrubs on landfill Some problems with trees	Grass and trees doing well over most of the site. Some trees were having problems on the site	Good
Dcb	Guilderland S.L.F. Guilderland, New York	No problems with vegetation on landfill	Nothing was planted on landfill. Volunteer vegetation having problems	Poor
Do	Day Island Landfill Eugene, Oregon	Good grass growth, Some trees dead	Mostly good grass growth but some dead spots. Number of dead trees on and adjacent to completed landfill	Good
Do	Union Bay Univ. of Washington Seattle, Washington	Good grass cover	Numerous poor or no growth areas associated with high concentrations of landfill gas	Poor
H	City of Idaho Falls S.L.F. Idaho Falls, Idaho	No problems growing grass on landfill	Grass growing well on landfill. Some problems with trees observed on landfill	Poor

(continued)

TABLE 8. (continued)

*CLIMATES	
Abbreviation	Description
Ar	Tropical wet
Bsh	Steppe semiarid, hot
Bsh-Bw	Steppe semiarid-arid, hot
Bsk	Steppe semiarid cold
Bw	Desert or arid
Cf	Subtropical humid
Cs	Subtropical dry summer
Dca	Temperate continental warm summer
Dcb	Temperate continental cool summer
Do	Temperate oceanic
H	Highland

SECTION VI

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MAIL SURVEY INQUIRY LETTER

RUTGERS

COOPERATIVE
EXTENSION SERVICE
COOK COLLEGE

P O BOX 231, NEW BRUNSWICK, N J 08903

Telephone (201) 932-9443

The Cooperative Extension Service in cooperation with the Department of Plant Biology of Cook College, Rutgers University, New Brunswick, New Jersey is undertaking a survey to determine the extent of problems associated with growing vegetation adjacent to and on top of completed solid waste refuse landfills. Here in New Jersey we have observed a number of cases where trees and other vegetation adjacent to landfills have been killed by the lateral migration of landfill gases. We have also experienced many problems in growing adequate ground cover, particularly the deeper rooted vegetation. on the soil covering completed landfills. We would like to know if you know of any similar problems.

We also expect to conduct field and laboratory studies to help determine the cause of these vegetation growth problems and how they may be surmounted. Your assistance in helping solve these problems by returning the enclosed questionnaire in the self-addressed postage paid envelope will be greatly appreciated. If you would like to receive a report on the results of this study, please check the item next to your name and address.

Very truly yours,

Franklin B. Flower
Extension Specialist in
Environmental Sciences

bc
Enc.

APPENDIX B

OMB No. 158S 75005
Approval Expires 6/76

QUESTIONNAIRE: TO DETERMINE THE EXTENT OF VEGETATION GROWTH PROBLEMS ASSOCIATED WITH SOLID WASTE REFUSE LANDFILLS

Do you know of completed refuse landfills where there have been problems in growing vegetation on their cover material? Yes_____ No_____

If yes, please list those landfills that have had the greatest problems.

NAME	ADDRESS

1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________

Do you know of refuse landfills where there have been problems of growing vegetation adjacent to the landfill? Yes_____ No_____

If yes, please list the landfills that have had the greatest problems.

NAME	ADDRESS

1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________

(continued)

APPENDIX B. (continued)

Do you know of completed refuse landfills that have been able to grow a good vegetative ground cover with few problems? Yes_______ No_______

If yes, please list those completed landfills that are growing good vegetative covers and the type of cover they are growing.

NAME AND ADDRESS	TYPE OF COVER: Grass	Shrubs	Trees	Other
1.				
2.				
3.				
4.				
5.				

If you have any comments on the effects of buried solid waste on living surface vegetation we would certainly appreciate hearing them. We would also appreciate your adding your name and address to this sheet and returning it to Frank Flower, Cook College, Rutgers University, New Brunswick, New Jersey 08903 in the enclosed self-addressed postage paid mailing envelope.

Name_______________________

Title_______________________

Address_______________________

____

____

_____Please send me a summary of the results of this refuse landfill - vegetation study when completed.

APPENDIX C

CLASSIFICATION OF MAIL SURVEY SOURCES

	ORGANIZATION	1975 Date Sent	Number Sent	Form Letter No.
1.	State Soil Conservation Service Offices	5/19	57	1
2.	County Agents and Selected Specialists in New Jersey	5/19	60	2
3.	State Cooperative Extension Service Directors.	5/20	63	3
4.	EPA-SWMP Regional Representatives	5/29	10	4
5.	State Solid Waste Management Agencies	5/30	58	5
6.	Publications	6/2	33	6
7.	S.W. Planning Cours. Registration, 6/13-15/7[illegible]	6/2	15	7
8.	APWA Educ. Fun. Ref. Col. and Disposal Workshop, 5/9-10/72 Reg.	6/2	19	7
9.	Sanitary Landfill Design Seminar, 6/28-29/73 Reg.	6/5	55	7
10.	New Jersey Conservation Districts	6/6	15	7
11.	Major Solid Waste Management Firms	6/6	10	7
12.	Engineering Foundation SLF Conf. 8/13-18/72 Reg.	6/12	81	7
13.	Other	6/5-12/31	130*	7
14.	Gas and Leachate from Landfill Conf. 3/25-26/75 Reg.	7/18	191	7
15.	Solid Waste Processing Div., ASME Membership	7/20	194	7
16.	New York State Soil Conservation Districts	9/25	12	7
		TOTAL	1,003	

* - Approximate number

APPENDIX D

LIST OF FIELD EQUIPMENT

1- compass
2- pen and note pads
3- 6' and 50' steel tapes
4- string
5- camera and film
6- vegetation I D books
7- roller tape
8- pail
9- clip board
10- felt marking pens
11- close up lenses for camera
12- hammer and mallet
13- screwdrivers
14- wrenches - adjustable and pipe
15- pliers - standard, long nose, water pump
16- garden trowel
17- tool boxes
18- masking tape
19- electrician's knife
20- plastic bags for soil samples
21- shovel
22- soil profile extractor
23- 3" soil auger
24- first aid kit
25- bags to carry equipment and supplies
26- gloves
27- insect repellent
28- boots
29- thermos
30- soil sampling procedure - SOP
31- gas sampling procedure - SOP
32- water sampling and testing procedures - SOP
33- files for reports
34- preaddressed mailers
35- refill for 3' bar hole maker
36- Explosimeter with extra catalyst and 10/1 dilution tube
37- O_2 analyzer
38- 20% CO_2 analyzer
39- 60% CO_2 analyzer
40- 3' thermometer
41- extra tips for bar hole maker
42- water analysis kit
43- 3' gas sampling probe
44- paper clips and rubber bands
45- rubber stoppers
46- O_2 and CO_2 refills
47- O_2 and CO_2 analyzer repair kits
48- Explosimeter calibration kit
49- 3' and 4' bar hole makers

APPENDIX E

LANDFILL-VEGETATION FIELD INSPECTION FORM

SITE: DATE:

Name
Address

Phone

CONTACTS:

Names
Addresses

Phones

LANDFILL:

Size
Cover (Quantity and Quality)
- Daily
- Intermediate
- Final

Refuse
- Type
- Depth

Degree of Compaction

TEMPERATURES: (°F. and Location)

Ground (3 ft. depth)
- Over Landfill - Good Growth -
- Poor Growth -
- Virgin Land -

Ambient (in shade) -

Settlement
Leachate
Odor
Age
- Started
- Completed

Cell Size
Current Use
Ultimate Use

(continued)

APPENDIX E. (continued)

Vegetation (Quantity and Quality) on Landfill

- Grass
- Shrubs
- Trees
- Other

Vegetation (Quantity and Quality) Adjacent to Landfill

- Grass
- Shrubs
- Trees
- Other

General Notes and Observations: (Include an outline map of area.)

APPENDIX F

FIELD GAS SAMPLE ANALYSIS FORM

*Soil Sample Taken

	COMBUSTIBLE GAS AT											
	1'			2'			3'			1'	1'	
SITE	LL	10/1	20/1	LL	10/1	20/1	LL	10/1	20/1	% O_2	% CO_2	REMARKS

APPENDIX G

FIELD SOIL SAMPLING PROCEDURE

a. Select and map site.
b. Locate sampling stations in areas of good and poor vegetation growth.
c. Take samples from three or four points within sampling stations to reduce the chance of taking samples from an unindigenous area.
d. Avoid surface contamination such as fertilizer or garbage. To avoid contamination when taking samples do so quickly and firmly. Without rotating the sampling tube insert the tube directly into the soil. A bucket can be used to transfer the soil from the sampler to the bag. Use 3" soil auger or garden trowel to obtain sample when sampling tube cannot be used.
e. Obtain a pint of both surface soil (topsoil)and subsoil for analysis. Fill two sampling bags. Take the surface soil sample first.
f. Measure the depth of the topsoil. If the topsoil is less than 8" deep take the surface soil sample from the first 8" of soil; if the topsoil is more than 8" deep take the surface soil sample from the total depth of the topsoil.
g. Take the subsoil sample from the next 8" of soil depth using the same hole(s) from which the topsoil sample was obtained.
h. At the time of sampling, characterize the soil as to whether it is wet, moist, or dry, by squeezing it. Water will drip from wet soil when squeezed, moist soil will remain as a ball, while dry soil will crumble after being squeezed
i. When putting the sample in the bags for transport to the soils laboratory be sure to seal them tightly to prevent water loss.

APPENDIX H

FIELD LEACHATE SAMPLING AND ANALYSIS PROCEDURE--

The following method for sampling leachate was established.

1. Secure a sample of the leachate in a glass or polyethylene bottle (100-200 cc).
2. If the solution is very dark, it may require dilution with distilled water before applying the color tests.
3. Test for the following components by methods described in the Hach Water Testing kit. Be sure to rinse the vials with distilled water after each test.
    a. pH
    b. Free and total acidity
    c. Alkalinity
    d. Copper content
    e. Iron content
    f Chloride content
4. Determine total conductivity by means of the Beckman Mho-Gun.

APPENDIX I

DETAILED OBSERVATIONS AND FIELD DATA FROM LANDFILL SITE SURVEY

AR-TROPICAL WET CLIMATE

San Juan Sanitary Landfill, Puerto Rico

In 1967 the San Juan Landfill, located seven miles south of the city of San Juan on Route #1, began accepting incinerated municipal refuse and light industrial refuse. In 1972, after the incinerator was closed, sanitary landfill operations began. The 100-acre landfill now accepts approximately 1700 tons/day of municipal and light industrial refuse which has reached a depth of eighty feet in some places.

The daily cover spread at the end of each day's landfilling ranged from zero to six inches during the period of time this site has been operated as a sanitary landfill. In areas where landfilling has been completed, the final cover ranged from six inches to twelve inches. Much of the refuse has been placed in a low lying marshy area, presumably above the water table. However, according to Charles Romney (Natural Resource Specialist, 1550 Ponce Leon Boulevard, San Juan, Puerto Rico) the majority of the refuse was dumped into the water lying in the marsh.

The completed portions of this landfill have not been planted with vegetation and are currently not being used by anyone. Volunteer vegetation has established itself in some areas where the final cover is the deepest. However, much of the area is devoid of vegetation. A continually burning landfill fire on the north side of the landfill was responsible for the death of a group of adjacent trees when the fire flared up and began burning the leaves on the trees.

One volunteer legume tree growing near the edge of the same face has died this year. Combustible gas at three feet beneath this tree was about seven percent. Twenty feet away and still on the edge of the refuse, was a living legume tree with no combustible gas in the root zone down to three feet. Soil samples were taken to better ascertain the cause of death.

Approximately 500 feet southeast of these legume trees was a group of cucurbit (cucumberlike) plants. In the area of good growth, no combustible gas was found at one foot, trace amounts were found at two feet, and ten percent at three feet. The gas at three feet probably has little if any effect on the growth and survival because of the shallow root system. In a generally barren area twenty feet away, combustible gas was found in trace amounts at one foot, and at two feet reached forty percent of the soil gas atmosphere.

In summary, combustible gas related positively to dead vegetation and bare cover soil.

Bayamon Sanitary Landfill, Puerto Rico

In 1970, the municipality of Bayamon began operating a sanitary landfill for the disposal of municipal solid waste. The landfill is located at Barrio Buena Vista, about four and a half miles south-southeast of Bayamon along Highway #167. Operations in the landfill were begun in 1970 and discontinued in 1974 by order of the United States District Court in San Juan, Puerto Rico, as a result of a lawsuit by residents of the area.

Prior to the closure of the landfill, and at the request of the United States District Court, the United States Geological Survey conducted a field test and collected and analyzed samples of the leachate flowing from the landfill (June and July 1972). The results of these analyses is reported in the proceedings Gas and Leachate from Landfills: Formation, Collection and Treatment, (EPA-600/9-76-004), United States Environmental Protection Agency, Cincinnati, Ohio.

The landfill covers approximately ten acres. No vegetation was planted on the landfill; however, thick grass covered most of the site and a few small volunteer trees and shrubs are scattered about the site. The combustible gas concentrations could not be determined beneath any of the trees or shrubs on the landfill because the ground contained too many rocks.

Adjacent to the landfill, on the south slope, were two large trees. One of these had lost all of its leaves during the previous year and another, forty feet away, was healthy. High combustible gas concentrations were found in the root zone of the dead tree but no combustible gas was found beneath the living tree. O_2 and CO_2 readings were similar beneath both trees and the soil temperatures averaged about 90°F.

Leachate was streaming from the bottom of the south slope of the landfill and running over the soil around a group of large trees growing adjacent to the refuse. Many of these trees have died, particularly the large ones in the area where the leachate is running.

In summary, no trees were planted on the landfill; however, volunteer grasses and shrubs have completely covered the area, but the cover was too rocky to obtain soil gas readings Adjacent to the landfill, combustible gas was found beneath a dead tree and no combustible gas was found beneath a living tree. A number of trees adjacent to the landfill have also apparently been killed by excessive leachate.

Cayey Sanitary Landfill, Puerto Rico

This forty to fifty acre operating landfill, located three miles east of Cayey off Route #1, receives approximately six tons of municipal and light industrial refuse every day from a few surrounding communities. Operation began in 1971 by filling a canyon. By March, 1977 it was up to eighty feet deep in the center. Daily cover is scraped off of an adjacent ridge on the north end of the area and placed over the refuse at the end of each day's operations. Approximately six inches to one foot of daily cover is used. No leachate or settlement was apparent.

No attempts have ever been made to vegetate this landfill. In addition, no volunteer plants occupied any part of this site. However, adjacent to the south side of the landfill is a sugar cane field which has been abandoned for reasons other than the landfill's impact. No migrating combustible gas was found in this field but the refuse has been adjacent to the field for only three months.

When the Cayey Sanitary Landfill is completed it is planned that tennis and basketball courts will be built and various trees and shrubs will be planted.

BS-STEPPE OR SEMIARID CLIMATE

Pioneer-Cannon Stakes Dairy, Salt Lake City, Utah

This former 150+ acre landfill was reported to be currently used as pasture land. Examination of the site revealed that the area is located in lowlands near the Great Salt Lake, where the salt water table is close to the surface. Municipal refuse had been deposited in this area with the hopes that it would raise the level of the soil above the water table so that the salt could be leached out of the soil.

Two fields were examined. The field completed in 1975 was planted in 1976 with alfalfa and sudan grass. Neither crop was observed growing at the time of our inspection. Instead only weeds were observed growing in this field. The second field had been completed as a landfill in 1966. This was the third year that a crop was planted on it. There was noticeably better growth in this field than in the first field.

Carbon dioxide and combustible gas concentrations were much higher and oxygen much lower in the poor vegetation growth field than in the better (second) field (Table J-1). Although the second field showed generally good growth there were large patches in the field where nothing was growing. Combustible gas readings were the same in the no-growth areas of this field as in the areas where the vegetation was doing very well. It is suspected that high salt concentrations may be responsible for these no growth areas.

Settlement was noticeable in both fields. The farmer who cultivates these fields reported that this settlement hinders the operation of the farm equipment. The settlement also leaves depressions that cause ponding. This is a problem because the ponded water collects salt from the subsoil which remains on the surface after the water evaporates.

TABLE I-1. PERCENT COMPOSITION* OF SOIL GASES IN FIELDS WITH GOOD AND POOR VEGETATIVE GROWTH

PIONEER-CANNON STAKES DAIRY, SALT LAKE CITY, UTAH

	Good Alfalfa Growth		Weeds Only	
Sample Depth	2'	3'	2'	3'
O_2	-	17	-	10
CO_2	-	<0.5	-	22
Combustible Gas	5	-	45	-

*Average of 2 to 11 readings

Timpanogos Golf Course, Provo, Utah

The Timpanogos Golf Course is located on South Street, east of Interstate 15, between East Street and University Avenue in Provo, Utah. Nine holes of the Golf Course were reported to be built over a former refuse landfill. When combustible gas checks were made in this area toward the south end of the course, it was apparent that no refuse had been placed in this area, since no combustible gas was detected. We were then informed by the golf course superintendent that only a small area between the tenth and fourteenth fareways had been filled with municipal refuse. This small area, which was filled in 1946, measures approximately 200 feet long and 35 feet wide with a maximum depth of six feet. Combustible gas reading at one spot was about thirteen percent of the soil gas atmosphere at the two foot depth. Here considerable settlement had resulted in very noticeable undulations of the ground surface. The grass in this and all other areas where refuse was placed was growing just as well as on that part of the golf course where there was no refuse. No combustible gas was recorded at one foot anywhere in the settled area. The irrigation of the grass probably promoted a shallow root system. This may explain the good grass growth despite the presence of combustible gas at the two foot depth in one location. The roots are probably growing above the combustible gas.

South Street Sanitary Landfill, Provo, Utah

This 100-acre landfill was completed in 1973 with the placement of municipal refuse in depths of ten to fifteen feet. One side of the landfill adjoins a major highway (Interstate 15). Russian olive trees were planted along this side of the landfill. Although these trees were reported to have been planted on the landfill, it was found that they had been planted on a soil dyke surrounding the landfill. The trees were in good condition and ranged in height from nine to twenty feet. No combustible gas was found along the 1,000 foot length of this tree planting. The soil appeared to be of a better quality where the trees were growing than that on the landfill where very little vegetation grew. At one point on the landfill the combustible gas concentration was found to be greater than fifty percent at the one and a half foot depth.

At this landfill the soil dyke apparently prevented the gases of anaerobic decomposition from migrating horizonatally out of the landfill.

Great Falls Sanitary Landfill, Great Falls, Montana

The 25+ acre Great Falls Sanitary Landfill began operation in 1963 with the acceptance of municipal refuse and some agricultural wastes. This continued until around 1973 when shredded refuse was also accepted. Shredded refuse was placed over that part of the landfill now occupied by a wheat field. Six inches of daily soil cover was placed over the non-shredded refuse, but no soil cover was spread over the shredded refuse until the end of the filling operations in 1975 when twelve to eighteen inches of final cover was spread.

In the fall of 1975, following the completion of the site, part of the former landfill was seeded with winter wheat as was an adjacent field on virgin land. According to the owner, the wheat germinated normally in the fall of 1975 and survived the winter as did the wheat planted on virgin land. However, with the onset of the summer dry period the wheat on the landfill began to show signs of chlorosis and remained stunted. Dieback was extensive. The total wheat yield from the landfill area was about one-half that normally expected from a field this size. It was reported that the wheat in certain areas of the refuse-filled area did not grow taller than three to four inches.

Combustible gas and CO_2 readings in these severely growth-stunted areas were higher and O_2 concentrations lower than in the areas of better growth (Table I-2). A very good correlation exists between the presence of combustible gas and stunting and dieback of the wheat plants.

TABLE I-2. PERCENT COMPOSITION OF SOIL GASES IN WHEAT FIELDS WITH GROWTH OF DIFFERENT QUALITIES

GREAT FALLS SANITARY LANDFILL, GREAT FALLS, MONTANA

	Excellent Growth*		Good Growth**		Poor Growth**	
Sample Depth	1'	3'	1'	3'	1'	3'
O_2	-	-	-	16	-	12
CO_2	-	-	-	12	-	21
Combustible Gas	0	-	0	-	12	-

*Off landfill
**On landfill

BW-DESERT OR ARID CLIMATE

Del-Rio Sanitary Landfill, Phoenix, Arizona

The thirty-five foot deep Del-Rio Sanitary Landfill, which covers 1/3 square mile, is presently operated by the city of Phoenix, Arizona. Some sections of the landfill have been completed. One of these areas adjacent to the scale house was planted with a number of cottonwood trees in 1974. Most of our investigative work was done here.

The landfill began operations in 1969 using a cell size of approximately 300'/64'/8' and accepting only municipal refuse. A caterpillar type bulldozer was used both to compact the refuse and spread the six inches of daily cover as well as the thirty inches of final cover. Because of the geologic history of the Phoenix area, the cover material contained many round rocks. Consequently, the soil in which the cottonwood trees were planted had to be imported from another area.

Five of the six cottonwood trees planted adjacent to the scale house were planted in 3' 6" inside diameter, 6' long cement drain pipes. These vertically set pipes extended two feet above the surface of the cover material. The sixth tree was not growing in a cement pipe but was planted in the cover material.

No combustible gas was found at any depth in these containers except for a trace in one container at three feet (Table I-3). Combustible gas averaged 1-2 percent at two feet beneath the tree not planted in the container. This tree appeared to be the most healthy of the six trees. Four of the five containers supported grass growth while no grass was growing in the fifth container. The cottonwood in this container has died and was the third tree of three which had been planted and died in that container. The poplars in the four other containers did not appear completely healthy, but they had grown this year and next year's buds appeared normal.

There appeared to be no correlation between combustible gas concentration and the health of the poplar trees. Although some combustible gas was present in the root zone of the mostly healthy poplar, it did not appear to effect the viability or growth of the tree.

TABLE I-3. PERCENT COMPOSITION* OF SOIL GASES AT DEAD AND LIVING POPLARS

DEL-RIC SANITARY LANDFILL, PHOENIX, ARIZONA

	Living Poplar		Dead Poplar	
Sample Depth	2'	3'	2'	3'
O_2	-	21	-	21
CO_2	-	2	-	1
Combustible Gas	1-2	-	0	-

*1-2 readings

Deer Valley Park, Phoenix, Arizona

Six acres of this landfill have been vegetated in anticipation of developing the site into a municipal golf course. There is six to eighteen feet of municipal refuse in the landfill with cover thickness ranging from about thirty inches to ten feet.

Bermuda grass was planted over the entire area and was observed to have difficulty growing on the site. There were many patches over the site where the grass wasn't growing. No correlation was found between these patches and the occurrence of landfill gases in the soil (Table I-4). There was also no visible difference in the growth of the grass between the area where the cover was thirty inches thick and where it was ten feet thick.

TABLE I-4. PERCENT COMPOSITION* OF SOIL GASES IN FIELDS WITH GOOD AND POOR GRASS GROWTH

DEER VALLEY PARK, PHOENIX, ARIZONA

	Good Growth		Poor Growth	
Sample Depth	1'	2'	1'	2'
O_2	20	-	20	-
CO_2	4	-	4	-
Combustible Gas	-	9	-	0.5

*1-2 readings

Adjacent to the landfill there was observed a number of dead and dying trees which had been transplanted to the site. Three of these trees were examined and combustible gas. About 2% was found at a three foot depth near only one of them.

It appears that the problems with the vegetation on and adjacent to this landfill are caused by something other than landfill gases, such as lack of water or poor soil conditions.

Johnson's Farm, Maricopa County, Arizona

This former sanitary landfill of 9.1 acres was completed in December 1970 after being operated for a year and four months. The landfill contains an average of nine feet of municipal refuse with thirty inches or less of cover material.

The site had been planted with barley for three to four years. The farmer reports that the yield from this area was one-fourth of the yield from adjacent virgin land. The plants were only half as high in this area, the roots were stunted and there was poorer germination in the field over the refuse. Settlement was also reported to be severe enough to hinder the operation of farm equipment and disrupt surface drainage.

At the time that this data was collected the field over the refuse was fallow. The farmer had given up in his attempts to farm the site. The soil appeared to be of noticeably poorer quality in the field over the refuse than the adjacent virgin land. There were barren patches among the weeds and barley that grew on the site. In these areas where nothing was growing combustible gas concentrations were found to range from four to five percent at a depth of one foot, and from fifteen to thirty percent at the three foot depth. In areas on the refuse where the vegetation was doing fairly well no combustible gas was found at the one to two foot depth. No combustible gas was found in the active farm field adjacent to the former landfill farm field (Table I-5). The farmer reported that the barley planted in the field off the landfill had grown much better than the barley on the landfill.

There does appear to be a positive relationship between the poorest barley growth and the presence of landfill gases.

TABLE I-5. PERCENT COMPOSITION* OF SOIL GASES IN BARLEY FIELDS WITH GOOD AND POOR GROWTH

JOHNSON FARM, MARICOPA COUNTY, ARIZONA

	Good Growth**		Fair-Poor Growth***		Very Poor Growth***	
Sample Depth	1'	3'	1'	2'	1'	3'
O_2	20	-	21	-	18	-
CO_2	0	-	0	-	5	-
Combustible Gas	0	0	0	0	5	23

*Average of 2 readings
**Off landfill
***On landfill

Glendale Nursing Home, Maricopa County, Arizona

The Glendale Nursing Home was built in 1975 on the site of a former sanitary landfill. The refuse was removed from the area where the building was located and replaced with clean fill and crushed rubble. However, the refuse remained beneath the area where landscaping plants were planted.

Landfilling with municipal refuse began on this site in 1966 and was completed in 1974 to a depth of approximately fifteen feet. Six inches of daily cover were spread at the end of each day's filling and about thirty inches of final cover was placed at the completion of the landfilling operations.

In the summer of 1976 the area surrounding the building was planted with grass and various tree species, including olive, orange, and palm trees. Silver dollar trees were planted in December 1976. Settlement areas in the lawn and in one of the parking lots accumulate water when the irrigation system is turned on. Despite frequent irrigation, approximately one-quarter of the trees planted were dead or showed signs of stress as of January 19, 1977.

No combustible gas was found beneath any of the trees on the site except for one trace reading at three feet under one living palm tree. However, carbon dioxide concentrations reached 9 percent and 4.5 percent beneath two dead silver dollar trees while no carbon dioxide was found beneath a living silver dollar. However, this situation was reversed beneath two olive trees where the highest CO_2 (8%) was found under a living olive tree and the lowest concentration (2%) beneath a dead olive tree (Table I-6).

TABLE I-6. PERCENT COMPOSITION* OF SOIL GASES BENEATH LIVING AND DEAD TREES

GLENDALE NURSING HOME, MARICOPA COUNTY, ARIZONA

	Living Trees		Dead Trees	
	Silver Dollar	Olive	Silver Dollar	Olive
Sample Depth	27"	36"	15"	36"
O_2	20.5	12	15	21
CO_2	0	8	7	2
Combustible Gas	0	0	0	0

*Average of 1-2 readings

No consistent relationship were found between vegetation survival and presence of combustible gas or carbon dioxide. The dead plants appear to have succumbed because of transplanting difficulties.

Cal Sutton's Farm, Maricopa County, Arizona

Since this thirty-eight acre sanitary landfill was completed in 1972 wheat, cotton, and barley have been grown on this site in alternate years with the aid of regular irrigation.

Municipal refuse was deposited in this area from December, 1970 to April, 1972 to a total depth of fourteen feet. Six inches of daily cover was spread over the refuse at the completion of each day's operation, and two to three feet of cover material was spread as a final cover.

The yield from this landfill field is as much as forty percent below that obtained from an adjacent field on virgin land. The soil on the former landfill field dried quicker, requiring more frequent irrigation, than the adjacent virgin field. Settlement has caused many undulations throughout the field forcing the farmer to fill in the settled areas with soil from unsettled areas of the field thereby creating a non-uniform soil depth throughout the field. Many of these settled areas supported little vegetation.

Combustible gas readings were taken in two good growth areas and two poor growth areas on the former landfill field. Most of the test points could not be penetrated beyond one foot because the soil contained many large rocks; however, three points were penetrated to three feet The soil became considerably softer and easier to penetrate at two feet indicating that perhaps the refuse began at this depth.

Very low combustible gas concentrations (averaging about two percent) were recorded at one foot in a poor barley growth area, and no combustible gas was found in the good growth areas. However, at three feet, the combustible gas concentration was about fifteen percent beneath the good growth area.

Barley growth on the former landfill was poor although very little combustible gas was found on the former landfill. Low combustible gas readings were found in the bad growth areas while the good growth areas contained almost no combustible gas in the topsoil (Table I-7). The extremely rocky hard soil over the former landfill probably contributed to the poor growth.

TABLE I-7. PERCENT COMPOSITION* OF SOIL GASES IN VARIOUS BARLEY GROWTH QUALITY AREAS

CAL SUTTON'S FARM, MARICOPA COUNTY, ARIZONA

	Adjacent to Former Landfill	On Former Landfill	
	Best Growth	Good Growth	Poor Growth
Sample Depth	3'	1'	1'
O_2	20	20	21
CO_2	0	1	0
Combustible Gas	0	trace	2.0

*Average of 1-2 readings

CF-SUBTROPICAL HUMID CLIMATE

Montgomery #2 Wareferry Road, East Montgomery, Alabama

This operating landfill was located in a former sand and gravel pit covering about thirty acres. It contains general municipal refuse to a depth of about twenty-five feet in most places. Adjacent to the landfill is a fifty-acre soybean field. The refuse nearest to the soybean field is about five years old.

The field was examined for possible landfill gas damage. The soybean plants on the edge of a dirt road separating the landfill from the soybeans were severely stunted, averaging about six inches high. Plants further in the field averaged three feet in height. This stunted area was approximately twenty feet wide and followed the edge of the road for the entire length of the field. The farmer felt that this stunting was caused by the farm equipment compacting the soil when it turned at the end of the field.

Combustible gas checks in these stunted areas revealed that a small amount of landfill gas was present. At a one-foot depth combustible gas comprised an average of one percent, no CO_2 was found and O_2 comprised twenty-one percent of the soil atmosphere. At a depth of three feet combustible gas averaged five percent of the soil atmosphere. A very slight odor was present one foot beneath the stunted plants.

The root systems of the stunted plants were compared with those from the normal growth area. The roots of the stunted plants extended three to four inches into the soil while those in the normal area reached down one foot.

Three other stunted areas within the main field up to 109 feet from the refuse were checked for combustible gas. No combustible gas was found in any of these areas. The stunting in these areas was probably due to ponding.

Another stunted area located along the edge of the field was examined. No combustible gas was found in this area. The lack of landfill gases in this area and the low concentrations of combustible gas where it was found and the lack of CO_2 where the combustible gas was found supports the farmer's opinion that the stunting was due to soil compaction.

Selma Sanitary Landfill, Route 80, Selma, Alabama

This small (three acre) landfill contains eight to ten feet of municipal and light industrial refuse. The refuse was only covered occasionally, resulting in an open-dump operation most of the time. This site was used from 1969 to 1973. Upon completion of landfilling the refuse was covered with two to three feet of soil and was planted with loblolly pine seedlings. When planted in 1973 these seedlings ranged from eighteen inches to over seven feet in height.

Very little combustible gas was present in the soil over the refuse. Of twenty-two test points only two contained combustible gas at a depth of one foot. The highest reading at a depth of two feet was about five percent, beneath a loblolly pine which was seventy-five inches high, one of the largest trees on the site. Since loblolly pine has a characteristically shallow lateral root system, two feet of soil should contain most of the roots. Although the tree heights ranged from eighteen inches to over seven feet, no correlations were found to exist between tree height and the presence of combustible gas. In general, the trees were doing as well as might be expected in similar soil not located over a former refuse landfill.

Montgomery #1 Sanitary Landfill, Montgomery, Alabama

This operating landfill was begun in the early 1960's. The refuse ranges from ten feet to fifteen feet deep over an area of approximately twenty acres. The daily cover ranges from zero to six inches, with a final cover of about two feet. However, some areas lacked adequate cover and the refuse remained exposed. Some areas on the landfill have remained flooded for long periods of time preventing any vegetation from growing. Settlement appeared to have caused the depressions in which the water accumulated.

Trees and shrubs covered the fifteen-year old portion of the landfill while shrubs, small trees and annual weeds have become established on the ten year old portion. No combustible gas (or occasionally very low combustible gas) concentrations were recorded in these vegetated areas. A positive correlation was found between high combustible gas concentrations and death of a Kentucky coffee tree, while low combustible gas was found beneath a living coffee tree (Table I-8).

TABLE I-8. PERCENT COMPOSITION* OF SOIL GASES BENEATH LIVING AND DEAD KENTUCKY COFFEE TREE

MONTGOMERY #1 SANITARY LANDFILL, MONTGOMERY, ALABAMA

	Living Tree		Dead Tree	
Sample Depth	1'	2'	1'	2'
O_2	21	-	20	-
CO_2	0	-	$\frac{1}{2}$	-
Combustible Gas	-	1	-	$12\frac{1}{2}$

*Average of 1-3 readings

Gautier Street Landfill, Tuskegee, Alabama

This three acre landfill operated from 1955 to 1970. The landfill contains municipal refuse ranging in depth from a few feet to about twenty feet. There are two to three feet of final cover.

Native forest vegetation is adjacent to the landfill on three sides. Volunteer vegetation from this forest was found growing on the site, particularly mimosa and loblolly pine. No attempts had been made to replant this landfill.

Two loblolly pine trees were checked for combustible gas in their root zones; one healthy tree, and one which exhibited severe dieback. Combustible gas readings were similar beneath these two trees. However, CO_2 was much higher under the unhealthy tree (Table I-9).

Four mimosa trees were compared; two were experiencing severe dieback, two were healthy. Combustible gas was higher on the average near the symptomatic trees. CO_2 was found to be higher near the unhealthy trees (Table I-9).

TABLE I-9. PERCENT COMPOSITION* OF SOIL GASES BENEATH HEALTHY AND UNHEALTHY TREES

GAUTIER STREET LANDFILL, TUSKEGEE, ALABAMA

	Healthy Trees				Unhealthy Trees			
	Loblolly Pine		Mimosa		Loblolly Pine		Mimosa	
Sample Depth	2'	3'	2'	3'	2'	3'	2'	3'
O_2	-	20½	-	18½	-	19	-	20
CO_2	-	0	-	2½	-	18	-	0
Combustible Gas	10	-	3½	-	4½	-	17½	-

*Average of 1-5 readings

Old Dothan City Landfill, Ashford, Alabama

This seven year old landfill accepted municipal refuse from the city of Ashford from 1970 to 1974. The refuse was deposited in trenches dug approximately fifteen-feet deep, thirty-three feet wide and up to 400-feet long. There is about two feet of final cover over this refuse.

Weeds covered most of the site. No trees, either volunteer or planted, were found growing on the landfill. There were a few dozen twenty-five to thirty-five year old loblolly pine trees adjacent to the eastern edge of the landfill. Two of the trees had been dead for more than a year while most of the other trees were reasonably healthy Many of the trees in this area had damage near the ground as would result from a fire years before.

The two dead trees were compared with two living trees (Table I-10). The combustible gas in the soil atmosphere near the dead trees at the one foot depth averaged 1½ percent and at the three foot depth 17½ percent. This was considerably higher than what was found near the healthy trees. Oxygen was found to be lower near the dead trees but more CO_2 was found near the living trees. The dead trees had evidence of cankering above the "fire damage". This might have been due to a disease. To what extent this could have contributed to the demise of the trees could not be determined. The data indicates that the trees could have been damaged by migrating landfill gases.

TABLE I-10. PERCENT COMPOSITION* OF SOIL GASES BENEATH LIVING AND DEAD LOBLOLLY PINE TREES

OLD DOTHAN CITY SANITARY LANDFILL, ASHFORD, ALABAMA

	Living Loblolly Pine Trees		Dead Loblolly Pine Trees	
Sample Depth	1'	3'	1'	3'
O_2	21	-	17	-
CO_2	$5\frac{1}{2}$	-	0	-
Combustible Gas	0	1	$1\frac{1}{2}$	$17\frac{1}{2}$

*Average of 1-8 readings from root zones of 2 dead and 2 live trees

Atmore Sanitary Landfill, Escambia County, Alabama

Landfilling began at this five-acre site in August, 1973 and continued until August, 1976. It accepts general municipal refuse and wood, which is burned. The refuse was placed in trenches about fifteen-feet deep and forty-feet wide and 300-feet to 400-feet long. It was covered daily with six inches of sandy soil. The final cover over the trenches is two feet deep. When completed the site is to be reclaimed as forest land.

The first trench was completed in February 1974 and was planted with fifteen-inch tall loblolly pine seedlings in March 1974. Over 1,000 trees were planted in rows six inches apart. Approximately twenty percent of these trees were dead or missing in August 1976. The living trees ranged from seventeen inches to over seven feet tall. These pines were judged to be doing fairly well compared with similar plantings on virgin soil by the local Soil Conservationist who is involved in reforestation projects throughout this county.

The soil atmospheres were compared between where the trees had grown very well, being seventy-seven inches to ninety-seven inches tall, and where the trees weren't growing well, being seventeen inches to thirty inches tall. Very little CO_2 was found anywhere on this landfill and O_2 concentrations were found to be about normal at a one foot depth near both groups of trees. Combustible gas concentrations were generally low at the one foot depth near all of the trees, but it was slightly higher near the poorly growing trees. At a three foot depth there was much more combustible gas near the poorly growing trees (Table I-11).

This data indicates that landfill gases may be hindering the growth of some of the trees, but not enough to noticeably reduce the overall success of the site.

TABLE I-11. PERCENT COMPOSITION* OF SOIL GASES BENEATH TALL AND SHORT LOBLOLLY PINE TREES

ATMORE SANITARY LANDFILL, ESCAMBIA COUNTY, ALABAMA

	77" to 97" Tall Loblolly Pines		17" to 30" Tall Loblolly Pines	
Sample Depth	1'	3'	1'	3'
O_2	21	-	21	-
CO_2	0	-	$\frac{1}{2}$	-
Combustible Gas	0	5	1	$11\frac{1}{2}$

*Average of 2-8 readings

Chatom City Landfill, Chatom, Alabama

The Chatom City landfill was begun in 1967 to enable household refuse to be brought here for open burning. The fill was completed in 1974 and was covered at that time with one to two feet of course,sandy soil. The entire site, including the adjacent cut over woodlot, which is used as a source of cover material, is five acres.

Slash pine trees were planted six feet apart over the entire site in 1974 in order to reclaim the land. The pines were planted as twelve inch seedlings. They were observed to range in height from twelve inches to forty-two inches in August, 1976.

No combustible gas was found in the soil anywhere on or adjacent to the landfill. In general, the trees planted over the area where the refuse had been open-burned were doing as well as the trees planted adjacent to the refuse. Apparently, landfill gas was not a problem here because the organics had been removed from the refuse by combustion prior to the final closing of the landfill in 1974.

CS-SUBTROPICAL DRY CLIMATE

City of Alameda Golf Course, Alameda, California

This eighteen-hole golf course was constructed on a completed refuse fill in 1955. Filling operations began sometime in the 1870's and ceased in 1953. The composition of the refuse is variable over the site, some areas having clean fill. About twenty feet of fill has been placed over bay muck.

Although in general the trees are growing well over the golf course, (eucalyptus are up to thirty feet tall), there are localized severe problems with vegetation growth and surface settlement. In one case, a 15 x 20-foot bare spot on a fairway contained combustible gas at the one-foot depth of greater than fifty percent. Adjacent to this spot are a number of Monterey pine trees which exhibited a good deal of variability in growth although all were planted in 1957. Almost no combustible gas was found in the root zone of these trees. The only combustible gas reading of any magnitude was $4\frac{1}{2}$ percent at a three-foot depth. The soil around these trees was not uniform. In some places it was extremely hard.

Poor drainage appears to be the greatest problem. Surface drainage is poor, particularly where extensive settlement has occurred. The dikes keep out the salty bay water, but the fresh water doesn't have any outlet because of these dikes and the dense nature of the clay subsurface soil. This area was examined during a severe drought, yet fresh water was found to be saturating the soil in several places at a depth of only one foot.

Galbraith Golf Course, Oakland, California

This golf course was constructed in 1966 on a 180-acre landfill completed in 1965. The landfill contains trash, rubble, and industrial waste in depths of fifteen to thirty feet. The cover-material depth ranges from zero to one foot. Settlement problems have occurred in some areas of the course. There has also been a large loss of trees, particularly pines, over the entire site. Some of these trees have blown over due to lack of a deep root structure; others were known to be killed by industrial waste; the cause of death for some was unknown.

Mounds of soil were deposited on the cover material along the fairways to provide for the growth of some trees. Other trees were planted directly in the cover material without mounds. It was noted that most of the trees in the mounds were eucalyptus while most of the pines had been planted directly in the cover material.

The most extensive vegetation growth problems occur on and around the eighth fairway. In this area the grass was growing poorly and much settlement was evident. At several points in this area the combustible gas concentration in the soil atmosphere at a one-foot depth was five percent or greater. Some of the pine trees along the fairway were doing much better than others, but combustible gas readings around several of these healthy trees were not significantly different than those around the poorly growing trees. Combustible gas at one foot depth near these trees ranged from 0 percent to about $5\frac{1}{2}$ percent, and at the two-foot depth it ranged from 0 percent to greater than fifty percent.

Some of the mounds are located in areas containing combustible gas. Data were collected to determine the ability of the mounds to provide gas-free soil for root growth. Two mounds were examined. Both were about thirty inches high at the center and about twenty-five feet in diameter. The eucalyptus trees on both mounds appeared to be growing rather well. In the cover material next to the mounds, combustible gas was found in two of six points tested at a one foot depth. At a two-foot depth these same six points all had combustible gas ranging from about five percent to greater than fifty percent. On one of the mounds combustible gas was absent down to a depth of two-feet six inches at three points. On the other mound no combustible gas was found at one and two-foot depths, but at a depth of three feet, concentrations were four percent to five percent.

The mounds were relatively free of gas to a depth of one foot; however, gas concentration was also very low in the cover soil. Therefore, the absence of appreciable gas in the root areas on the mounds may have been due to the cover soil serving as a barrier to the gas.

Oakland Scavenger Company, Davis Street Sanitary Landfill, San Leandro, California

This 247-acre landfill receives most of the municipal refuse generated in the Oakland-San Leandro area. The landfilling was begun around 1950, and is scheduled to be completed in 1977 or 1978. The twenty to forty feet deep landfill will then be converted into a golf course.

At the time of this inspection the only vegetation on the site was located along the bay front, which was landscaped in 1969 to reduce the eyesore created by the operating landfill. Four species of trees: Monterey pine, cypress, and two species of eucalyptus(red gum and blue gum) have been planted. A shrub, bottle brush, was also found here. At first this site was not irrigated and problems of poor tree growth were attributed to lack of water. After an irrigation system was installed, in early January 1976, many of the trees which were having growing problems showed improvement.

Two large eucalyptus did not improve and appeared to be dead. No refuse, or to be more accurate, no differential texture that would indicate refuse in this area was encountered in penetrating the soil at these eucalypti with a bar-hole maker. This, in conjunction with the lack of any combustible gas in the soil atmosphere, indicates that these eucalyptus trees were probably not on the landfill but on the dike which had been constructed to keep out bay water.

Some of the trees located on the refuse showed stress symptoms, most noticeably chlorosis (browning of the needles in pine) and stunting. Soil gas readings were taken near four Monterey pines, two of which were healthy and two unhealthy (Table I-12). Similar readings were taken for a healthy and an unhealthy cypress (Table I-12).

The data collected near the pine trees indicates a possible positive relationship between the occurrence of combustible gas and stress symptoms. The data collected near the cypress are inconclusive due to the very low concentrations of combustible gas.

TABLE I-12. PERCENT COMPOSITION* OF SOIL GASES BENEATH HEALTHY AND UNHEALTHY TREES

OAKLAND SCAVENGER COMPANY-DAVIS STREET SANITARY LANDFILL, SAN LEANDRO, CALIFORNIA

	Healthy Trees				Unhealthy Trees			
	Monterey Pine		Cypress		Monterey Pine		Cypress	
Sample Depth	1'	2'	1'	2'	1'	2'	1'	2'
O_2	$19\frac{1}{2}$	-	-	-	20	-	21	-
CO_2	$4\frac{1}{2}$	-	-	-	0	-	0	-
Combustible Gas	-	$5\frac{1}{2}$	-	0	-	$20\frac{1}{2}$	-	trace

*Average of 1-8 readings

Marine Park Golf Course, San Leandro, California

Nine holes of this eighteen hole golf course have been constructed on a completed landfill. The filling operations ceased in 1967 and the course was completed in 1972. Most of the refuse consisted of nonputrescible construction debris and paper deposited to a depth not exceeding twenty feet. Two to three feet of clay were put over the refuse as cover.

The golf course has not experienced problems with settlement or excessive loss of vegetation. A wide variety of trees and shrubs are growing over the site. Eucalyptus trees, many of which are over twenty feet tall, were the most noticable species. One area where several large pine trees had died was pointed out by the grounds-keepers. No combustible gas was found in this area. Mr. Frank Green, superintendent, attributed much of this loss to the roots growing into the refuse.

One area was reported to have some sewage sludge deposited in it. A variety of trees was growing in this area and appeared to be doing well, as was the grass. The only apparent interference with good grass growth was that caused by puddling in areas of poor drainage.

At a depth of two feet, throughout an area where healthy eucalypti were growing, combustible gas readings ranged from trace to over fifty percent at nine of the eleven sampling points. At a one-foot depth only two of these eleven points had any combustible gas (approximately two percent and five percent). These data indicate that the heavy clay cover-material was probably effective in containing the landfill gases.

Mountain View Sanitary Landfill, Mountain View, California

This operating landfill will be converted to a golf course when completed. The entire area has been reclaimed from San Francisco Bay by diking. The refuse ranges in depth from twenty-five feet to about forty feet and the cover material, while variable over the site, averages about two feet. A 1200#/cubic yard refuse density is said to be obtained in the landfill.

Three areas were examined. The first had a variety of eucalyptus species, planted by the University of California in about five feet of cover. These seemed to be doing well. Seven points were sampled in this area but only one contained combustible gas, and that was at a depth of three feet.

The second area examined had a row of eucalyptus trees which were planted on the most inland dike. Many of these trees were dead and most of those still living were experiencing severe dieback. The soil in this area was very hard and dry. Two of the dead trees were checked for combustible gas. None was found.

The third area examined was a 380' x 290' nursery of young trees which are to be transplanted when the golf course is landscaped. This area is on the refuse and the cover consists of one foot of compacted clay underlying two feet of loam, into which sewage sludge was incorporated. The trees are irrigated. These plantings are expected to help in the selection of tree species for planting on the golf course. The plot is laid out in a grid pattern containing twenty-five species and nineteen individuals of each species. The different species varied in their reaction to this situation, some being healthier than others. The redwood trees Sequoia gigantea and S. sempervirens had the greatest problem adjusting; all had died.

The feature of interest was not the ability of the different trees to grow here, but rather the ability of the clay layer to contain the landfill gas. Of thirty-two combustible gas readings taken at a one-foot depth, only five recorded the presence of combustible gas (ranging from a trace to about fifty percent). The four high readings were all obtained from within a forty-five foot long oblong area near the edge of the plot. Of fourteen combustible gas readings taken at two-foot depths, only two contained combustible gas, and that was only at trace concentrations. At a depth of three feet, all thirteeen points tested contained combustible gas. The readings ranged from a trace to greater than fifty percent.

South Coast Botanic Garden, Palos Verdes, California

The South Coast Botanic Garden is located on the Palos Verdes peninsula. It was constructed on an eighty-seven acre former landfill having a maximum depth of 165 feet. The landfill was constructed from 1957 to 1965 in a former diatomaceous-earth mine which had operated from 1929 to 1954. Diatomacecus earth was used as landfill cover.

The Botanic Garden, which was begun in 1961, is one of the first to be developed on a completed sanitary landfill. It boasts of 140 plant families, about 700 genera and over 2,000 species, with a total of more than 150,000 plants. The entire garden, with the exception of a concrete-lined pond was placed over a former municipal and industrial waste landfill.

The garden was observed to be well vegetated and presented a pleasing appearance. Problems establishing vegetation on the site were reported, these include wind toppling trees, settlement, and high soil temperatures. This survey confirmed the problems that were reported. Of particular interest was the occurrence of high soil temperatures which were apparently excluding the growth of vegetation in at least one area (Table I-13). Operators of the garden blamed many vegetation losses upon high soil temperatures but not on landfill gases. However, high concentrations of landfill gases were frequently found associated with high soil temperatures.

TABLE I-13. PERCENT COMPOSITION OF SOIL GASES AND SOIL TEMPERATURES AT HEALTHY AND DEAD OR POORLY GROWING VEGETATION

SOUTH COAST BOTANIC GARDEN, PALOS VERDES, CALIFORNIA

	Healthy Vegetation						Dead or Poorly Growing Vegetation					
	African Daisy			Hybrid Broom *Cytisis racemosis*			African Daisy			Hybrid Broom *Cytisis racemosis*		
Sample Depth	1'	13"	36"	1'	13"	36"	1'	13"	36"	1'	13"	36"
O_2	11	-	-	19½	-	-	14	-	-	11½	-	-
CO_2	16½	-	-	0	-	-	13½	-	-	15	-	-
Combustible Gas	2½	-	-	0	-	-	>15	-	-	22	-	-
Temperature °F	-	88	109	-	61	73	-	99	130	-	102	104

Note: Ambient air temperature = 50°F @ 8:45 am and 65°F @ 2:30 pm

In this survey of the Garden, combustible gas and elevated levels of carbon dioxide were found at a depth of one foot in several areas. An examination of the soil atmospheres near four living and two dead acacia trees revealed a possible correlation between the death of the trees and the presence of landfill gases in the soil atmosphere (Table I-14). There was also evidence of a canker disease on some of these trees both living and dead. To what extent this disease contributed to the demise of these trees could not be determined in these uncontrolled field conditions.

An area where grass was observed to be growing very poorly or not at all was compared with an area where the grass was doing very well. Combustible gas and carbon dioxide were found to be much higher in the soil where the grass wasn't growing well (Table I-14).

TABLE I-14. PERCENT COMPOSITION* OF SOIL GASES AND SOIL TEMPERATURES** AT HEALTHY AND UNHEALTHY VEGETATION

SOUTH COAST BOTANIC GARDEN, PALOS VERDES, CALIFORNIA

	Healthy				Unhealthy			
	Acacia Trees		Grass		Acacia Trees		Grass	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	18½	-	19½	-	13	-	17	-
CO_2	2	-	0	-	12	-	7	-
Combustible Gas	½	-	1½	-	19	-	11	-
Temperature °F	-	60	-	57	-	78	-	64

*Average of 4-11 readings
**Single readings

It appeared that much of the success of the vegetation growth was associated with the lack of landfill gases in the root zone. This may have been due to the diatomaceous earth cover-material acting as a gas barrier.

South Coast County Park, Palos Verdes, California

South Coast County Park is located across Crenshaw Boulevard from the South Coast Botanic Garden. It currently consists of a twenty-five acre former landfill tract which is being used as a park. Ultimately the park will cover 173 acres of former landfill, and it will include an eighteen hole golf course plus other recreational facilities. Some settlement has occurred and migration of combustible gas into an adjacent church building south of the landfill had to be corrected by venting through an induced draft system. This gas is burned in an outdoor flare.

Manhattan rye grass planted on the site appears green and luxuriant. Some planted trees are underlain with a layer of large gravel and vented with vertical 4 1/4 I.D. plastic pipe to a depth of two feet. The area is well irrigated, fertilized, and aerated. The soil temperatures fell between 50° to 57° F.

Landfill gas is extracted from this site by Reserve Synthetic Fuels, Inc., who produce pipeline quality methane for sale to the local gas company.

Data are presented in Table 1-15 comparing two sets of planted trees. In both cases, high concentrations of combustible gas were found in the root zone of the poorly growing trees while very little was found in the root zones of the healthy trees.

TABLE 1-15. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY VEGETATION

SOUTH COAST COUNTY PARK, PALOS VERDES, CALIFORNIA

	Healthy Vegetation				Dead or Chlorotic Vegetation			
	Melaleuca		Aleppo Pine		Melaleuca		Aleppo Pine	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	7	-	17	-	3½	-	11	-
CO_2	5	-	½	-	43	-	25	-
Combustible Gas	4	5	<1	>50	>50	>50	>50	>50

*Single readings

Mountain Gate Golf Course, Santa Monica, Los Angeles, California

Mountain Gate Golf Course is a privately owned eighteen-hole executive golf course which was built on the site of a landfill (Mission Canyon #4 and #5) which operated from 1965 to 1972. Plantings of Pinus halepensis (Aleppo pine), Eucalyptus, Myaporum, Acacia, Ficus and other species were established in 1973. Grass types consist of Penncross Bent on the greens, Seaside Bent on collars, and Bermuda grass on the fareways.

Extensive settling has been experienced on the golf course, amounting to as much as eleven feet in a single year. Daylight cracks are observable between landfill and non-landfill areas. The main irrigation lines are buried only in virgin ground. They are elevated above ground in the refuse deposition area. Flexible couplings and elevators permit movement within the piping system as settling occurs. Still there are about two breaks per week in the feeder lines as a result of uneven settlement of the underground pipes. The seven greens in the refuse deposition areas are underlain with four to five-inch thick concrete slabs, buried 2½ to 3 feet in the ground. A four to five-inch-deep layer of one-inch stone overlays the concrete slabs. Still, high combustible gas readings were observed in the soils of the greens. It has been estimated by the golf course construction superintendent that costs of maintenance of a golf course on a landfill (including irrigation, repair of daylight cracks and piping, drainage, etc.) are twenty percent higher than on a conventional course.

The soil atmospheres in areas where the vegetation was growing well were compared with that in areas where the vegetation was growing poorly. Two two-needle pine trees were compared, one of which was dead and the other alive. The combustible gas in the soil near each of the trees was about the same but CO_2 was lower and O_2 was higher near the tree which was living (Table I-16). Where aleppo pines and Eucalyptus trees were growing poorly landfill gases were found in the soil atmosphere, and where these trees were growing well no landfill gases were found (Table I-16).

TABLE I-16. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY VEGETATION

MOUNTAIN GATE GOLF COURSE, SANTA MONICA, CALIFORNIA

	Healthy Vegetation		Dead or Poor Growth Vegetation	
	Two-Needle Pine	Aleppo Pine & Eucalyptus	Two-Needle Pine	Aleppo Pine & Eucalyptus
Sample Depth	1'	1'	1'	1'
O_2	14	20	9	$9\frac{1}{2}$
CO_2	$7\frac{1}{2}$	0	$12\frac{1}{2}$	5
Combustible Gas	5-15	0	5-15	>50

*Single readings

Mission Canyons #1, 2, and 3, Los Angeles, California

In June, 1960, the County Sanitation Districts of Los Angeles County commenced sanitary landfilling operations in Mission Canyons 1, 2, and 3, located in the Santa Monica mountains in northwestern Los Angeles (Figure I-1.). Operations continued until October, 1965 when they were shifted southerly to Mission Canyons 4 and 5 which were to become Mountain Gate Golf Course.

By January of 1976 a grass cover had been established on MC #1; MC #2 had been planted along its easterly side with a 50 to 100-foot wide landscaped buffer zone; and MC #3 had been developed into a park containing grass, shrubbery, and trees.

Deposition of refuse in MC #1 was completed in 1963. Three or more feet of cover was reported to have been placed over this ten acre area, which is now planted with mixed grasses including alfalfa. These grasses, which are irrigated regularly, appear to be healthy. However, there are continuing problems with extensive, uneven settlement and with "daylight

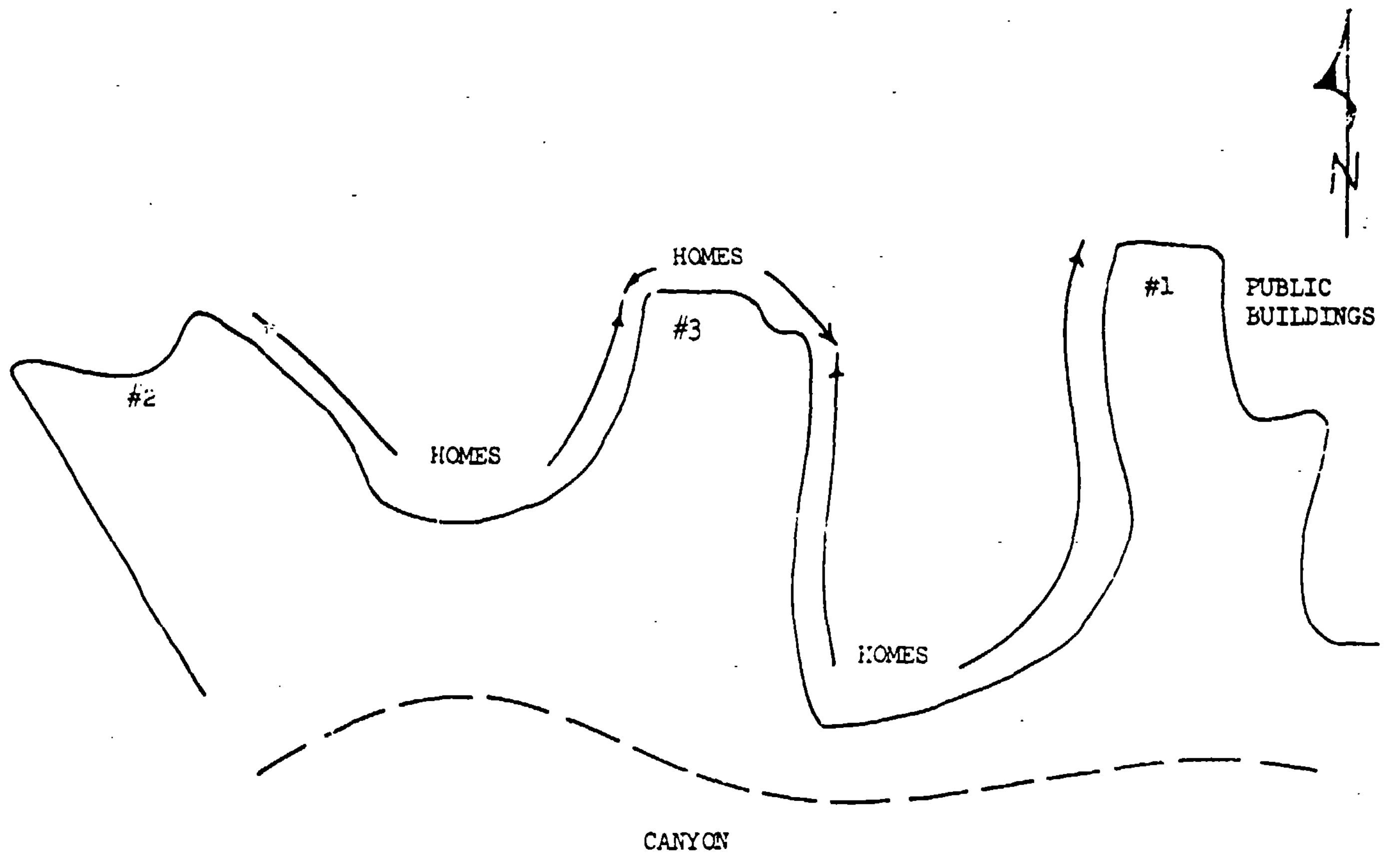

Figure I-1. Mission Canyon Landfills 1, 2, and 3, North Sepulveda Blvd,. Los Angeles, California cracks" along the interface of the refuse and virgin ground.

Mission Canyon #2 is a fifteen acre tract atop a landfill started in 1962 and completed in 1965. Currently one and-a-half acres along the eastern boundary have been developed toward its ultimate use as an aesthetic barrier between adjacent, developed residential areas and future landfill operations. Plantings of 1973, which are located primarily on a seven to eight-foot deep berm at the eastern edge of the refuse, appear to be growing well. This may be due, at least in part, to the presence of five operating gas-extraction wells on the tract. These wells were installed to prevent lateral gas migration. Two ground gas checks in the vicinity of the landscape barrier revealed only very minor amounts of combustible gas in the soil atmospheres.

Mission Canyon #3 is a ten-acre park built on a landfill that was constructed between 1960 and 1965. The refuse is reported to be as deep as 200 feet in places. Grass has been planted over the park along with scattered trees. The main plantings were Eucalyptus and Pinus plus a few Acacia.

The surface of this park was originally graded to promote drainage towards the periphery of the park. Since the original landscaping in 1973 settlement has reversed this grade so that at the present time most of the runoff is carried towards the center of the park. Here the refuse is deepest and settlement has been most extensive.

Table I-17 presents field data. In general, little combustible gas was found in the soil atmosphere until the three foot-depth was reached. This may have been due, at least in part, to the ten gas-extraction wells located around this site. Landfill gases were not found in the root zones of the vegetation. The gases collected are burned in a waste-gas burner located near the bottom of Mission Canyon. The trees and grass in general appeared to be growing fairly well. However, there were a number of bare spots in the lawn, a few of the trees were doing poorly, and a majority of the pines appeared chlorotic. In places the soil was water-logged at the time of our visit, apparently because of recent irrigation.

TABLE I-17. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY VEGETATION

MISSION CANYON #3, LOS ANGELES, CALIFORNIA

	Healthy Vegetation			Unhealthy Vegetation		
	Eucalyptus	Two-Needle Pine	Grass	Eucalyptus	Two-Needle Pine	Grass
Sample Depth	1'	1'	1'	1'	1'	1'
O_2	$20\frac{1}{2}$	21	21	$17\frac{1}{2}$	$20\frac{1}{2}$	21
CO_2	0	0	0	$1\frac{1}{2}$	2	0
Combustible Gas	0	0	0	0	$<\frac{1}{2}$	<1

*Average of 1-4 readings

Dca-TEMPERATE CONTINENTAL WARM SUMMER

Hunter Farm, Cinnaminson, New Jersey

The 100-acre landfill across the street from the Hunter Farm was reported to have been started in 1965 in an old sand-and gravel-pit. The fill material is 40-80 feet deep and consists of all types of refuse. The refuse was placed directly across the road from the farm beginning about 1969. Damage to farm crops was first noted in 1970.

At the time of this inspection, the farm field across the street to the southwest of the landfill was planted with corn. Approximately 250 feet away from the landfill was an irregularly shaped area of corn exhibiting severe stunting and chlorosis. The surrounding corn looked very healthy.

The dimensions of the chlorotic and stunted zone in the field were determined and soil atmosphere was checked for the presence of combustible gases, oxygen and carbon dioxide. Approximately thirty rows of the corn exhibited poor growth. A transect was made along which combustible gas, oxygen and CO_2 were measured at the one-foot and three-foot depths respectively, at fifteen foot intervals. The good growth areas contained no combustible gas while the area which exhibited chlorosis and stunting contained an average of fifteen percent combustible gas (Table I-18). The CO_2 concentration was much higher and the O_2 concentration considerably lower in the area of poor growth. Overall, we found positive relationship between the presence of decomposition gases and poor corn growth.

TABLE I-18. PERCENT COMPOSITION* OF SOIL GASES AT HEALTHY AND UNHEALTHY CORN

HUNTER FARM, CINNAMINSON, NEW JERSEY

	Good Corn Growth		Poor Corn Growth	
Sample Depth	1'	3'	1'	3'
O_2	13½	-	3½	-
CO_2	4½	-	20	-
Combustible Gas	-	0	-	15

*Average of 2 readings

DeEugenio Brothers Peachtree Farm, Glassboro, New Jersey

Landfilling at this site adjacent to the peach orchard began in February, 1968. The filled material included refuse collected from household collections plus some demolition material, industrial waste and sewage sludge. The landfill is located in a former sand-and gravel-pit which had a depth of about twenty feet. Upon completion of the landfill, the peach farmer had hoped to plant additional peach trees over the filled area by enlarging the adjacent orchard. However, in 1971, two years after the completion of the filling operations adjacent to the N-E side of the orchard, peach trees closest to the refuse filled area began to die. One year later soil gas measurements were made, and combustible gases and CO_2 were detected beneath many of the dead trees.

By June 1975, many additional trees had died. Soil gas checks in the area revealed that combustible gas was beneath a chlorotic, mostly defoliated mature peach tree, while no combustible gas was found beneath the adjacent mature peach tree which showed moderate growth (Table I-19).

New seedlings had been planted on the southeast side of the landfill and the trees in the row closest to the landfill had all died. Combustible gas was present beneath a dead tree in this first row, but it was not present beneath a living tree in the second row away from the refuse. The presence of combustible gas was found to be directly related to the death of peach trees in this orchard adjacent to the refuse landfill.

TABLE I-19. PERCENTAGE COMPOSITION* OF SOIL GASES VS PEACH TREE VIABILITY

DE EUGENIO PEACH ORCHARD, GLASSBORO, NEW JERSEY

	Good Growth Trees				Poor Growth or Dead Trees			
	Saplings		Mature		Saplings		Mature	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	19	-	20	-	19	-	16½	-
CO_2	0	-	0	-	0	-	5½	-
Combustible Gas	-	0	-	0	-	5	-	>15

*All readings are single samples

University of Connecticut, Storrs, Connecticut

The University of Connecticut began a project in 1970 to determine if corn could be grown over a completed landfill. One hundred and fifty foot long trenches thirty feet wide and about ten feet deep were spaced thirty feet apart and filled with mostly newspapers. A corn crop was subsequently planted over the trenches and intertrench areas. The project ran out of funds at this time. However, a decrease in corn yield was observed over the trenches as compared to the intertrench areas. The soil over the trench areas was also reported to be of poorer quality.

In 1975, alfalfa and clover were planted over this area. Our field observations of these crops showed a significant decrease in flower height over the trench areas (Table I-20). Some sample stations in the trench (poor growth) area contained combustible gas at three feet while other sample stations contained no combustible gas. No sample stations in the intertrench (good growth) areas contained combustible gas. Therefore, in some cases, the presence of combustible gas related directly to poor vegetation growth while in other cases there was no correlation between poor growth and the presence of combustible gas.

TABLE I-20. PERCENT COMPOSITION* OF SOIL GASES AT AREAS OF GOOD AND POOR GROWTH, ALFALFA AND VETCH

UNIVERSITY OF CONNECTICUT, STORRS, CONNECTICUT

	Good Growth	Poor Growth
Sample Depth	3'	3'
O_2	17½	20
CO_2	0	0
Combustible Gas	0	0-33

*Average of 1-9 readings

Farmington Sanitary Landfill, Unionville, Connecticut

This landfill contains an average of about twenty-five feet of municipal refuse covered with about two feet of soil. The landfill was completed in 1973.

The area examined had been planted with about 200 Scotch pine trees. Few of them were still living when this data was collected. Lack of care and competition from volunteer species, particularly quaking aspen, might account for their demise. A good deal of variation was noted in the condition and dispersal of the quaking aspens over the site. A negative relation was found between the presence of combustible gas and CO_2 and the condition and dispersal of aspens. Several patches of tall (5 to 8 feet) dense stands of aspens were observed. In other areas the aspens were under four feet tall and scattered, or they weren't growing at all. Where the quaking aspens were doing well no combustible gas was found at the one-foot depth and an average of ½ percent CO_2 and 19 percent O_2 was found in the soil atmosphere. Where the trees weren't growing, or were growing poorly, the soil atmosphere contained, on the average, about 1 percent combustible gas, 9 percent CO_2 and 14 percent O_2 at the one-foot depth (Table I-21).

This data is consistent with the possibility that the presence of landfill gases hindered the establishment of the aspens on this site.

TABLE I-21. PERCENT COMPOSITION* OF SOIL GASES AT AREAS OF HEALTHY AND POOR GROWING QUAKING ASPENS

FARMINGTON SANITARY LANDFILL, UNIONVILLE, CONNECTICUT

	Healthy Aspens	Poor Growing Aspens
Sample Depth	1'	1'
O_2	19	14
CO_2	$\frac{1}{2}$	9
Combustible Gas	0	1

*Average of 3 readings

Holyoke Sanitary Landfill #1, Holyoke, Massachusetts

This landfill was begun in 1960 and was still in operation when this data was collected. The refuse is about forty feet deep and consists almost entirely of incinerator ash.

No attempts had been made to establish vegetation on the site. Dead trees were observed adjacent to the landfill. No combustible gas was found on or adjacent to the site indicating that very little anaerobic decomposition was taking place in the refuse. The trees had apparently been killed by soil eroding from the site.

Holyoke Sanitary Landfill #2, Holyoke, Massachusetts

This landfill operated from 1969 through 1973. It contains municipal refuse mixed with incinerator ash to depths of 120 feet in some places.

Of interest at this site were some black cherry trees growing adjacent to the refuse on virgin soil. A good relationship can be seen between death of black cherry and the percent of combustible gas in the soil atmosphere. Under two dead black cherry trees combustible gas in the root zone averaged $10\frac{1}{2}$ percent of the soil atmosphere at a three-foot depth. Combustible gas concentrations were higher near the tree which had died this year as compared with the tree which had been dead for over a year. Under a live black cherry, twenty feet from the dead trees, no combustible gas was found (Table I-22).

There was very little vegetation growing on the landfill. Nothing was planted and very small patches of voluntary weed species were seeding themselves. The cover material on the landfill was very dry and rocky; no topsoil had been put on it. In some areas the cover had eroded exposing the refuse.

TABLE I 22. PERCENT COMPOSITION* OF SOIL GASES AT LIVING AND DEAD BLACK CHERRY TREES

HOLYOKE SANITARY LANDFILL #2, HOLYOKE, MASSACHUSETTS

	Living Cherry		Dead Cherry	
Sample Depth	1'	3'	1'	3'
O_2	19	-	19	-
CO_2	0	-	$\frac{1}{2}$	-
Combustible Gas	-	0	-	$10\frac{1}{2}$

*Average of 1-7 readings

Erlton Park, Cherry Hill, New Jersey

This 9-10 acre completed sanitary landfill was formerly a sand and gravel pit. General municipal refuse was deposited here, beginning in 1963, to a depth of ten to sixty feet. Dumping was completed in 1970, and efforts to turn the site into a park were begun.

It appeared that less than half of the original trees planted at this park in 1974 were still alive. However, today's tests did not indicate any particular relationship between the presence or absence of combustible gas in the root zone and death or life of the vegetation (Table I-23). In most instances no combustible gas was found in the root zones of either the live or the dead trees. The high rate of tree death may have been due to poor tree-planting practice.

Hard soil layers were noted below the one-foot depth over much of the park. These layers may be keeping the gas from the tree roots and sending it to the vents around the periphery of the former landfill.

TABLE I-23. PERCENT COMBUSTIBLE GAS IN SOIL GASES AT LIVING AND DEAD TREES

EARLTON PARK, CHERRY HILL, NEW JERSEY

	Living Trees						Dead Trees							
	Two-Needle Pine		Poplar		Spruce		Two-Needle Pine			Poplar			Fir	
Sample Depth	1'	1½'	1'	2'	1'	2'	1'	2'	3'	1'	2'	3'	1'	2'
	0	<1	0	0	0	0	0	0	>50	0	0	0	0	0

Kenilworth Demonstration Landfill, Washington, D.C.

The completed landfill is about thirty feet deep and covers approximately 250 acres. It was started in 1942 with only incinerator ash. From 1969 to 1970 a project described as a period of model landfill operations was conducted during which time raw household refuse, as well as incinerator ash, were deposited. The entire area was then completed with a final twenty-four to thirty inch deep soil cover.

Between 1970 and 1975 about 200 trees were planted. These included red oak, sugar maple, and willow. The trees were not irrigated after planting. At least fifty percent of the trees showed signs of chlorosis with many of these being partially or completely defoliated at the time of our visit. Combustible gas checks in the root zones of all but two trees failed to reveal combustible gas. Many of these trees had apparently died from lack of water. The two trees with combustible gas in the root zone were entirely defoliated. A relation between dead trees and the presence of combustible gas existed in some, but not all instances (Table I-24).

TABLE I-24. PERCENT COMPOSITION* OF SOIL GASES AT LIVING AND DEAD TREES

KENILWORTH DEMONSTRATION LANDFILL, WASHINGTON, D.C.

	Living Trees		Dead Trees	
	Sugar Maple	Sweetgum	Sugar Maple	Sweetgum
Sample Depth	1'	1'	1'	1'
O_2	18	-	5	-
CO_2	0	-	12	-
Combustible Gas	0	0	>5	0

*Average of 1-2 readings

Holtsville Sanitary Landfill, Brookhaven, New York

This former landfill covers approximately fifteen acres. Landfilling began around 1955 in an old sand and gravel pit. All types of refuse were accepted including municipal waste, industrial waste and some burned material. The refuse was placed thirty to forty feet below the ground surface and twenty to thirty feet above the surface over part of the landfill. One to six inches of daily cover were spread over the refuse at the end of each day's landfilling operation. The future of this landfill as a park was considered when the final cover was being spread. One foot of sand was placed directly over the refuse and one foot of loam was spread over the sand for the promotion of good grass growth.

Over the former refuse fill area there is a general growth of grass and weeds. Grasses appear to dominate. The area is presently unused, but it is to be developed into a park. There is a parking lot to the south of the fill area and a wood lot on the west side. Dead and dying oaks and pines were observed on the south and west sides adjacent to the refuse.

An excellent relationship (Table I-25) was found between the presence of combustible gas in the soil and the death of deeper rooted vegetation (oak and pines approximately twenty-five years old) adjacent to the landfill. No combustible gases were found in the root zone of viable vegetation, but high concentrations were found in the root zones of the dead trees adjacent to the landfill.

TABLE I-25. PERCENT COMPOSITION* OF SOIL GASES AT LIVE AND DEAD RED OAKS

HOLTSVILLE SANITARY LANDFILL, HOLTSVILLE, NEW YORK

	Live Red Oaks				Dead Red Oaks			
	First Tree		Second Tree		First Tree		Second Tree	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	-	12	-	18	-	4	-	12
CO_2	-	9	-	0	-	28	-	10
Combustible Gas	0	-	0	-	40	-	>50	-

*Average of 1-3 readings

Kings Park Sanitary Landfill, Smithtown, New York

The twenty-three acre landfill, which was begun in 1971 in a former sand and gravel pit, was still in operation at the time this data was collected. The refuse is of a general municipal type and averages about sixty feet in depth. No vegetation was observed growing on the landfill.

Adjacent to the landfill, on the south side, many dead large oak trees were observed in a woodlot, located between the landfill and Old Northport Road. A dead white oak about thirty feet tall was compared with a living white oak of about the same size. Both trees were located in the woodlot. A dead hemlock six feet tall was compared with a living hemlock seven feet tall. Both hemlocks were planted in 1970 by the city on the edge of the woodlot nearest the road. Soil atmosphere concentrations of combustible gas and carbon dioxide were found in much greater concentrations in the root zones of the dead trees than in the root zones of live trees. Oxygen concentrations in the soil were much lower at the dead trees than at the live trees (Table I-26).

TABLE I-26. PERCENT COMPOSITION* OF SOIL GASES AT LIVE AND DEAD TREES

KINGS PARK SANITARY LANDFILL, KINGS PARK, NEW YORK

	Live Trees				Dead Trees			
	White Oak		Hemlock		White Oak		Hemlock	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	-	11	-	20	-	4	-	6½
CO_2	-	8	-	2	-	32	-	19½
Combustible Gas	1-2	-	0	-	>50	-	7½	-

*Average of 1-3 readings

Huntington Sanitary Landfill, Huntington, New York

It had been reported that many large oak trees adjacent to this landfill had been killed. An on-site investigation revealed dead trees adjacent to, and around most of the landfill. The incinerator ash and municipal refuse had been placed in a fifty-five foot deep former sand and gravel pit. An area near the southeast corner of the landfill along Town Line Road was chosen for this investigation.

A comparison of the soil atmospheres at the living and dead oak trees adjacent to the landfill (Table I-27) show that extremely high carbon dioxide and combustible gas readings were associated with the dead oaks. Generally lower oxygen concentrations were found in the soil atmospheres at the dead trees than at the live trees. In many cases it was found that the soil beneath the dead trees was septic at the depth of six inches while that beneath the live trees was aerobic. The dead trees on the west side of Town Line Road closest to the landfill didn't have any leaves. The dead trees on the east side of the road still held their dead leaves indicating that the trees farthest from the landfill had died more recently than those nearer the landfill.

Soil temperatures were higher where the higher combustible gas and carbon dioxide and low oxygen concentrations were found (Table I-27).

A limited number of vertical convection vents had been installed along the southern end of the landfill, but trace amounts of combustible gas were found 130 feet from the landfill in the adjacent wood lot. The soil around this landfill is very sandy. This apparently facilitates the movement of the gases generated within the landfill into the adjacent undisturbed land.

TABLE I-27. PERCENT COMPOSITION* OF SOIL GASES AND SOIL TEMPERATURES** AT LIVING AND DEAD TREES

HUNTINGTON LANDFILL, HUNTINGTON, NEW YORK

	Living Trees				Dead Trees			
	Red Oak		Scarlet Oak		Red Oak		Scarlet Oak	
Sample Depth	1'	3'	1'	3'	1'	3'	1'	3'
O_2	-	12	-	-	-	8½	-	8
CO_2	-	9½	-	-	-	35	-	40
Combustible Gas	4	-	0	-	50	-	30	-
Temperature °F	64	-	58	-	65	-	78	-

*Average of 1-3 readings
**Single readings

Bethpage Sanitary Landfill, Oyster Bay, New York

This forty acre landfill is located in a very sandy soil region of Long Island. The landfill contains general municipal refuse, ash, and demolition debris which has been placed in a former sand and gravel pit that averages about forty feet deep. In many areas the refuse is piled to a total depth of sixty to eighty feet. Adjacent to the easterly side of the landfill and across Winding Road is a bridle trail. It was noted that most of the mature red and white oaks (40 to 50 feet in height) in the area were dead, but most of the understory vegetation was living.

Near the dead oaks, both combustible gas at one foot and carbon dioxide at three feet were very high (35 to 40%) and oxygen readings at three feet were low (5 to 10%). Landfill gases appear to have migrated to about seventy feet from the landfill. No live trees were accessible for comparison with the dead oaks.

It appears that the demise of the native trees in this area was due to the pollution of the soil by gases migrating underground from the landfill across the street. The understory vegetation may still be living because of its shallower root system.

Dcb - TEMPERATE CONTINENTAL COOL SUMMER CLIMATE

Roussel Park, Haines Road, Nashua, New Hampshire

This site had been an open dump which was covered with five feet of gravel, on top of which was placed six inches of loam. The refuse is ten to twelve feet thick and consists mostly of municipal type refuse. The cover material has been planted with grass which was observed to be providing adaquate cover. Two baseball parks and a monument have been established on the site.

Correlation between the presence of combustible gas and death of American elm and slippery elm (located adjacent to the refuse) was not very good. At a depth of three feet, comparable concentrations (0% to 40% of the soil atmosphere) of combustible gas were found under healthy trees and dead trees. There was also a dead tree near which no combustible gas was found. The possibility exists that combustible gas, present at an earlier time, killed the tree, and has subsequently left this tree's root zone. Dutch elm disease is also very prevalent in this region, although its characteristic symptoms were not noticeable on this dead tree.

In the root zone of one slippery elm there was found between fifteen percent and thirty-five percent combustible gas in the soil atmosphere at 2' and 3' respectively. There was a small branch on this tree with yellowing leaves which appeared symptomatic of Dutch elm disease.

Oxygen concentrations at one foot were about normal (18%) under both living and dead trees. Under one dead elm a CO_2 concentration of 2.5% was recorded at a one-foot depth. The highest combustible gas concentrations (40%) were recorded at this spot at a three foot depth, but no combustible gas was noted at a one-foot depth in this area.

In summary, correlation between the presence of landfill gas in the soil atmospheres and dead trees was poor at this site.

Guilderland Landfill, Guilderland, New York

This landfill was still operating when this data was collected. The area of the landfill where the data was collected was completed in 1971. The landfill contains municipal refuse on top of which there is about two feet of cover material. This area had been seeded with rye grass but with poor success.

Volunteer species were observed growing on the site, most notably: quaking aspens, staghorn sumac, milkweed, and Queen Anne's lace. This volunteer vegetation, along with the rye grass, was observed to be occurring in isolated clumps with bare and sparsely vegetated areas between. The areas where the vegetation was growing well were compared with the areas where the vegetation was growing poorly or not at all. Combustible gas and CO_2 concentrations at a depth of one foot in the soil were considerably higher where the vegetation wasn't growing well. Oxygen concentrations at a one foot depth were very low in the poor growth areas averaging only 2.5% of the soil atmosphere as compared with 16.4% in the good growth areas (Table I-28). The data indicates that the composition of the soil atmosphere on this landfill was probably playing a major role in determining where the vegetation was able to establish itself.

TABLE I-28. PERCENT COMPOSITION* OF SOIL GASES AT GOOD AND POOR GROWTH VEGETATION

GUILDERLAND LANDFILL, GUILDERLAND, NEW YORK

	Good Growth	Poor Growth
Sample Depth	1'	1'
O_2	16½	2½
CO_2	2½	34½
Combustible Gas	3	40½

*Average of 4 - 10 readings

City of Auburn North Division Street Sanitary Landfill, Auburn, New York

This landfill was operating at the time this data was collected. The area on the landfill with which this report is concerned was completed about fifteen years ago and is estimated to contain about twenty feet of municipal refuse. The cover appeared to range in depth from two to three feet. Grass was doing very well on the site as were many of the trees which had become established on the site.

Of particular interest was a row of willow trees which were showing wide variations in growth. There was a negative correlation between the height of the willow trees and the concentrations of combustible gas in the soil atmosphere. There were three distinct height categories with different gas concentrations in their root zones. At the two-foot depth, the willows which were twenty feet high had an average of less than one percent combustible gas in the soil atmosphere; the ten-foot high trees had an average of 8 5% combustible gas at the two-foot depth; and in the area where the trees had died and been removed, the soil atmosphere contained an average of 30.5% combustible gas at a two-foot depth (Table I-29).

The fact that increased combustible gas in the soil atmosphere correlated with a decrease in the height of the tree may indicate an adverse response to the presence of combustible gas in the soil atmosphere.

TABLE I-29. PERCENT COMPOSITION* OF SOIL GASES AT WILLOW TREES SHOWING VARIOUS GROWTH CHARACTERISTICS

CITY OF AUBURN NORTH DIVISION STREET SANITARY LANDFILL, AUBURN, NEW YORK

	20' Tall and Healthy		10' Tall		Dead and Removed	
Sample Depth	1'	2'	1'	2'	1'	2'
O_2	20	-	19	-	$18\frac{1}{2}$	-
CO_2	0	-	$\frac{1}{2}$	-	$\frac{1}{2}$	-
Combustible Gas	-	1	-	$8\frac{1}{2}$	-	$30\frac{1}{2}$

*Average of 2-4 readings

South Eastern Oakland Incinerator Authority, Oakland County, Michigan

This landfill was completed in a former sand and gravel pit in 1968 and contains an average of about thirty-five feet of municipal refuse mixed with incinerator ash. This landfill has had problems with landfill gases migrating into adjacent property, particularly on the western edge. It was in this area that this data was collected, in and around a row of lombardy poplars planted adjacent to the landfill. Most of the lombardy poplars were dead at the time that this data was collected.

A negative correlation between weed and grass growth and combustible gas present at one foot was very good. There was no combustible gas present at one foot where the weeds and grass were growing well. At spots where there was no weed or grass growth, combustible gas averaged twenty-two percent of the soil atmosphere at the one foot depth. Also in these bare areas O_2 averaged nine percent of the soil atmosphere and CO_2 averaged 4.5% of the soil atmosphere at the one foot depth. These are, respectively, far below and above normal soil gas concentrations. When these gas concentrations are compared with those found in the areas where grass and weeds were growing well a sharp contrast is observed (Table I-30).

All the lombardy poplars which have died and subsequently sprouted were found to contain considerable amounts (between 5 and 50% of the soil atmosphere) of combustible gas in the root zone at the two-foot depth. At no time was a dead tree observed with no combustible gas in the soil atmosphere. Two mature (70 ft. tall) black oaks were observed to be in rapid decline within twenty feet of the landfill. At no point at a three foot depth near these trees was less than fifty percent combustible gas found in the soil atmosphere.

A trend was seen here in the pattern of necrosis on the three species of plants observed dying at this site. When combustible gas was present in the soil and necrosis was seen on the foliage, the dieback of the leaves usually began at the tips of the branches and progressed down towards the base of the plant.

TABLE I-30. PERCENT COMPOSITION* OF SOIL GASES AT GOOD GROUND COVER AND NO VEGETATION GROWTH AREAS

SOUTHEAST OAKLAND INCINERATOR AUTHORITY LANDFILL, OAKLAND, MICHIGAN

	Weeds and Grass Growing Well	No Weed or Grass Growth
Sample Depth	1'	1'
O_2	20	9
CO_2	0	$4\frac{1}{2}$
Combustible Gas	$\frac{1}{2}$	$22\frac{1}{2}$

*Average of 2-9 readings

Cereal City Landfill #1, Battle Creek, Michigan

This landfill has been operating since 1956. It contains an average of about twenty-four feet of municipal refuse covered with about two feet of sandy soil where completed. No attempts had been made to vegetate this cover. This landfill has a history of gas migrating into adjacent property. This report concerns a row of red pine trees which had been transplanted to the northern edge of the landfill less than ten feet from the refuse in this former sand and gravel pit.

There is a negative correlation between the occurrence of landfill gases and the health of the trees. Where the trees were dead for over two years, the average percent combustible gas concentrations in the soil atmosphere were 22.7% at the one-foot depth and 49% at the three-foot depth. The O_2 concentrations averaged 12% and the CO_2 averaged 17.5% at a depth of one foot. In the area where the trees were living but experiencing some needle necrosis, the combustible gas averaged .25% at a one-foot depth and 15% at a three-foot depth. The CO_2 and O_2 concentrations were, respectively, 6.5% and 19.5% at a depth of one foot (Table I-31).

TABLE I-31. PERCENT COMPOSITION* OF SOIL GASES AT LIVING AND DEAD RED PINE TREES

CEREAL CITY LANDFILL, BATTLE CREEK, MICHIGAN

	Living Red Pine**		Dead Red Pine**	
Sample Depth	1'	3'	1'	3'
O_2	19½	-	12	-
CO_2	6½	-	17½	-
Combustible Gas	½	15	22½	49

*Average of 1-8 readings
**Weeds and grass growing well near live tree, no grass or weed growth near dead tree.

Cereal City Landfill #2, Battle Creek, Michigan

This landfill has been in operation since 1956. It contains an average of about twenty-four feet of municipal refuse covered with about two feet of sandy soil. No attempts have been made to vegetate this cover. This landfill has a history of gas migrating onto adjacent property. This report is concerned with a row of mixed hardwood and coniferous trees located along the southwest corner of the landfill. Most of these trees, adjacent to this former sand and gravel pit, were observed to be in decline and many were dead.

There appears to be an excellent correlation between the presence of combustible gas in the root zone of the planted trees and death or decline of these trees. This was found to be true for white spruce, Douglas fir, white fir and shagbark hickory. The amount of combustible gas in the root zones of these trees at the one foot depth varied between 5% and 50% (with a mean of 25.6%) of the atmosphere. There were two live white spruce trees under which the combustible gas concentrations ranged from 10% to greater than 50% (with a mean of 29.5%) of the soil atmosphere at the one-foot depth. These trees may not have been exposed to the landfill gases as long as the trees which had been killed, or they could be resistant or have shallow roots.

A very putrid-smelling, hard soil layer, three inches thick, was present in the virgin soil where high combustible gas concentrations were found. The top of this layer was found five inches below the surface, and it was not present where combustible gas was not found.

Kalamazoo County Landfill, Kl Avenue, Oshtemo Township, Michigan

This landfill has been operating since 1965. It contains municipal and light industrial refuse ranging in depth from eighteen to forty feet. The final cover was generally two feet thick, but noticeably thinner in some areas. The completed landfill was planted with clover and fescue with reasonable success. An area which had recently been planted with Kentucky 31 Fescue was doing very poorly; the cover material in this area was very thin and dry.

In one area of the landfill a quaking aspen, which was showing no signs of stress, had an average of 8.4% combustible gas in the soil atmosphere at a one foot depth, O_2 comprised 18.5% and CO_2 3.5% of the soil atmosphere at a one foot depth.

Do - TEMPERATE OCEANIC CLIMATE

East Campus, University of Washington, Seattle, Washington

From 1926 to 1955 parts of this 150 acre peat bog area served as an open-burning dump for the city of Seattle. In 1956 "modern" sanitary landfill methods were started. The rate of filling the marshland accelerated from the late 50's until 1966 when filling ceased. However, a series of surface cover filling, grading and seeding operations altered the landscape, until 1971, when all but minimal maintenance activities ceased. Today the central part of this area supports a grassy prairie-like cover bordered by peat islands, cattails and occasional trees along the shoreline.

Settlement over the area has been extensive. It is reported that portions of the site dropped six feet between 1971 and 1975. Part of this settlement is believed to be due to the decomposition and compression of the underlying former peat bogs.

Gas checks over the grasslands area revealed no combustible gas to a depth of three feet in an area where the grass and weed ground cover was growing very well. In an area within forty-five feet of the good growth area, where no grass or other ground cover was growing, combustible gases were found at high concentrations (>15%) at the one, two and three-foot depths. The soils in the no-growth area below the four inch depth were dark and emitted a septic odor. The soils in the good growth area were not septic. They emitted the normal pleasant soil odor. The areas in the grasslands which did not contain any vegetation also exhibited numerous cracks in the surface. In many cases it was noted that the unpleasant odors of the gases of anaerobic decomposition were being emitted from these cracks. It was reported that children have frequently set fire to these gases.

In random checks of the soil atmospheres in the root zones of various trees growing over the refuse filled area outside the grasslands section, combustible gases were not generally found in the atmosphere of soil less than two feet deep.

In the vicinity of the golf driving range, where a number of trees were checked, combustible gases were found in a number of cases at the two-foot depth and below. These combustible gases were present although the last refuse filling was reported to have been completed in this area prior to 1950. The trees in general appeared to be growing fairly well in this area.

In general, there was an excellent correlation in the "grasslands area" between poor and no vegetation ground cover and the presence of combustible gases within one foot of the surface. Where the combustible gases were below the two-foot depth the ground cover was doing very well.

Genesee Street Landfill Park Development, Seattle, Washington

This former landfill covers approximately sixty acres. Filling began in 1947 and was completed about 1968. The area north of Genesee Street was completed in 1963. That south of Genesee Street was completed in 1968. General landfill refuse was deposited in the fill along with a large amount of demolition debris and ash from the open burned refuse. The refuse varies in thickness from a few feet to about thirty feet. The cover material depth ranges from about two to about six feet. The material used for final cover was mostly glacial till. Substantial settlement has been reported during the last few years, along with some mounding of ground water in part of the fill.

Over the former refuse fill area there is a general growth of grasses and weeds. Grasses appear to dominate. The area is mowed about twice each year. The north end of the field area is occasionally used as a parking area. Most of the rest of the fill area is unused in any developed or planned manner. There are some peat deposits and soft clays beneath part of the fill area. It is believed that these peat deposits may be compacting due to the subcharging by the refuse and cover material.

Scattered barren spots were noted over the surface of the ground at various locations. These barren areas frequently contained many surface cracks, and occasionally the odors of the gases of anaerobic decomposition of organic matter in the landfill were detected. The soils from these barren combustible gas-laden areas were found to be soft, wet, dark-colored, and emitting septic odors. The soils where good grass and tree growth were taking place did not contain combustible gas, was dry and hard, and did not emit septic odors.

An oval area approximately 20'/9', had no vegetation growing on it. It was found to have a very high combustible gas concentration (>15%) at one foot. Soil from the six inch to eight inch depth was dark colored, had a putrid odor, and was anaerobic. The soil 16½ feet away in an area of good growing vegetation ground cover showed no combustible gases at the one and two-foot depths. Soil samples taken to an eleven inch depth were light-colored, friable, and exhibited no anaerobic odor.

No combustible gas was found at the three-foot depth under a big-leaf maple tree growing near the sidewalk along the north side of Genesee Street. At about sixty feet to the north a barren area, around 12'/27', was checked for combustible gas. It was found to contain high concentrations of combustible gas in the soil atmosphere.

Overall, an excellent correlation was found between the presence of combustible gases in the soil and the lack of surface vegetation. No combustible gases were found in the root zone of viable vegetation.

Day Island Landfill, Eugene, Oregon

This sixty-acre landfill is located in a former sand and gravel pit on the northeast side of the Willamette River. Between 1963 and 1974 the area was filled to depths ranging from twelve to thirty feet with general municipal refuse and construction rubble.

Currently a good general grass and weed growth covers most of the landfill. Some of the grasses were three to four feet high. However, there were numerous small areas where no ground cover existed. The no-growth station was found to have high concentrations of combustible gas at the one-foot depth, and the soil was septic at the three-inch depth. At a nearby good growth station there was no combustible gas to sixteen inches and the soil was aerobic (Table I-32).

The soil atmospheres of trees planted for landscaping purposes was checked, and combustible gas was found in the root zone of a dead tree, but it was not present in the root zones of two living trees. The soil was also septic in the root zone of the dead tree, but aerobic in the root zones of the live trees.

An area of dead and dying trees east of the landfill was surveyed. Here high concentrations of combustible gas were found in the soil atmospheres within seventy feet of the landfill where the trees were dead or dying. One-hundred and twenty feet from the landfill, the fifty-to sixty-foot tall trees were growing very well, and no combustible gas was present in the soil atmospheres.

As can be seen from Table I-32, there is an excellent correlation between the presence of landfill gases in the vegetation root zone and poor or no vegetation growth.

Soil temperatures were measured on and off the landfill and in gas and no-gas areas. The results are plotted in Figure I-2. In general, the temperature decreased with increasing depth. The highest temperatures were found where combustible gases were present on and off the landfill. The lowest temperatures were found off the landfill in the area where no combustible gases were present.

TABLE I-32. PERCENT COMBUSTIBLE GAS IN SOIL ATMOSPHERES AT LIVING, DYING, AND DEAD VEGETATION

DAY ISLAND LANDFILL, EUGENE, OREGON

	Sample Location	Description of Vegetation	Approximate % Combustible Gas Concentration At Various Depths	Soil Condition
Living Vegetation	Adjacent Ld-Fl	Healthy trees and grass.	0 at 1' and 3'	-
	On Ld-Fl	Grass and weed cover growing very well.	0 at 1' and 16"	Very hard below 16"
	On Ld-Fl	A living but not thriving black oak planted two years previous.	0 at 1' and 2'; >15 at 3'	Topsoil: light gray-brown, pleasant odor, barely moist.
	On Ld-Fl	A living but not thriving broadleaf maple planted two years previous.	0 at 1' and 2'	Hard ground below 2'
Dead and Dying Vegetation	Adjacent Ld-Fl	Grass and weeds doing poorly Many large dead trees.	>15 at 3'	-
	Adjacent Ld-Fl	Good grass cover. Dead white ash & broadleaf maple trees.	0 at 1'; 5-15 at 3'	-
	Adjacent Ld-Fl	Scattered live brush & grass Quite a bit of barren soil; Scattered dead & dying trees.	5-15 at 1' >15 at 3'	-
	On Ld-Fl	Barren, no vegetation. Barren, no vegetation.	5-15 at 1' and 16"	Septic odor, dark colored & damp; very hard below 16"
	On Ld-Fl	Dead red oak that was planted two years previous.	5-15 at 1'; >15 at 30"	Septic odor, black and wet

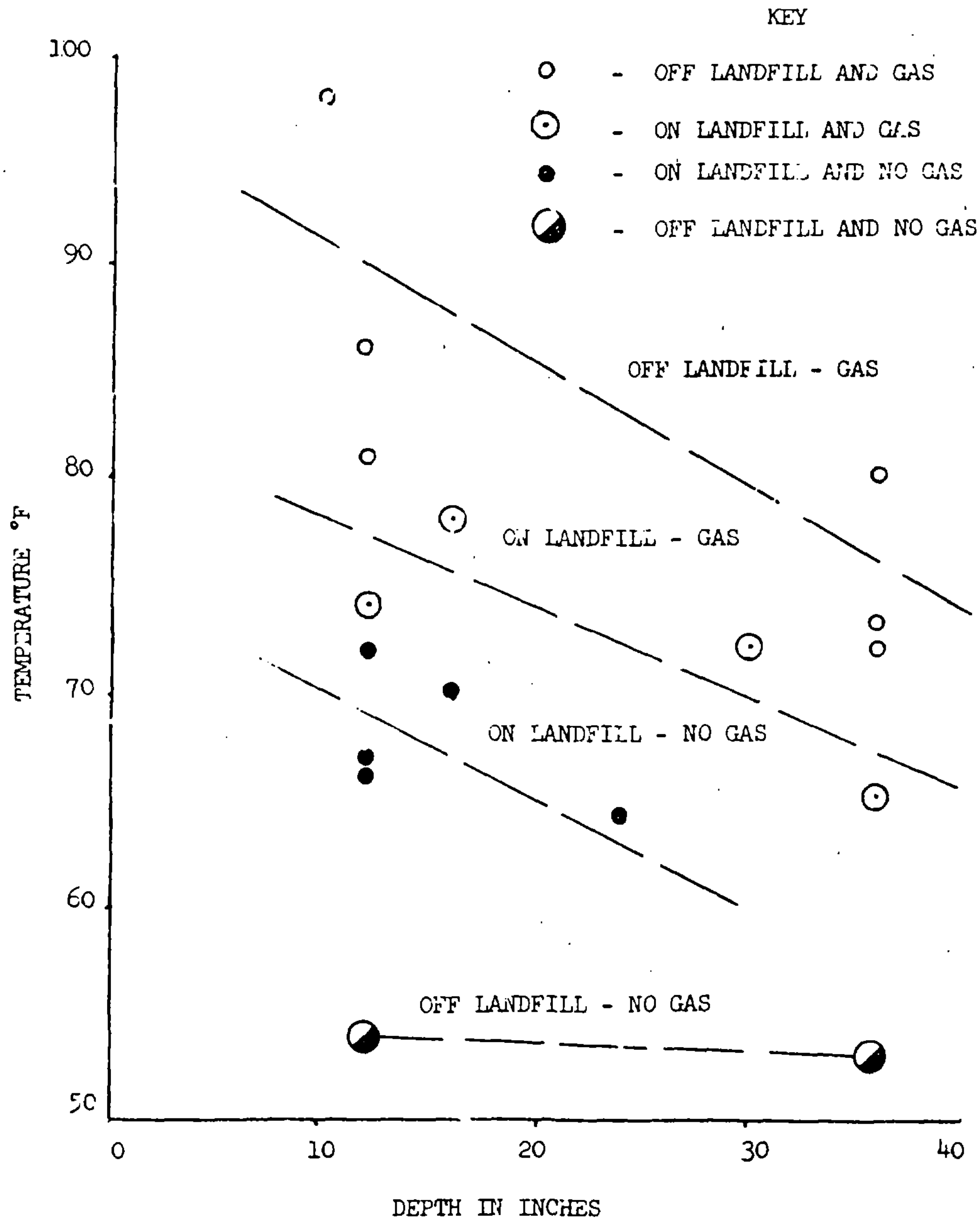

Figure I-2. Soil temperatures, Day Island Landfill, June 24, 1976

John Fowler's Farm, West Salem, Oregon

Approximately two acres of John Fowler's wheat field is located over about twenty feet of demolition waste that was deposited in 1968-69. This is a small section of a much larger wheat field. The wheat growing over the former landfill appeared to be almost as healthy as that growing in the virgin soil, non-refuse area. Combustible gas was found at less than half the test stations and then only at very low concentrations. However, there were some areas where surface settlement had been so extensive that the area could not be cultivated until it was refilled and replanted. Farmer Fowler also reported that he experiences difficulty in maintaining an adequate water supply in the soil over this refuse area because the shallow soil cover tends to dry out quickly between waterings.

Table I-33 summarizes the data obtained from the test stations. The soil was very hard at many of the test stations located over the former demolition landfill.

TABLE I-33. PERCENT COMBUSTIBLE GAS IN SOIL ATMOSPHERES IN WHEAT FIELD

JOHN FOWLER'S FARM, WEST SALEM, OREGON

Sample Location	Vegetation Quality	Combustible Gas Readings	Soil Condition
On Ld-Fl	13-15" tall wheat	0 at 3'	Hard to very hard
On Ld-Fl	10-21" tall wheat	Minor at 21"	Damp and dark brown extremely hard below
On Ld-Fl	13-31" tall wheat	0 at 3'	Soft
On Ld-Fl	14-20" tall wheat	0 at 8"	Rocklike at 8 inch depth
On Ld-Fl	11-23" tall wheat	0 at 1'	Hard object at 1'
On Ld-Fl (In Settled Area)	Scattered weeds (in settled area)	Trace at 2'	Soft to 33"
Adjacent Ld-Fl	12-27" tall wheat	0 at 3'	Varying from hard to soft

NOTE: Many small green aphid-like insects and many potato beetles were visible on the wheat.

H - HIGHLAND CLIMATE

Freemont Park, Idaho Falls, Idaho

This 15-17 acre site was a dump where open burning was practiced for forty years prior to it being converted into a sanitary landfill in 1970. Landfilling with municipal refuse was practiced from 1970 through 1972. The unburned refuse ranged in depth from 0 to 15 feet. After the landfilling ceased the process of converting the site into a park began and was still proceeding at the time that this data was collected. Due to variability in the composition of the refuse, a good deal of variability in the stability of the soil and landfill gas concentrations would be expected over the site.

In general, the grass was growing well throughout the park. However, many trees seemed to be having growth problems. Many dead and dying specimens were observed. Some of the deaths were apparently due to poor planting practices; in one case the root ball of a ten-foot high cypress tree was only half buried.

Data was collected, comparing trees which appeared to be dead or severely stressed with trees of similar size that were not exhibiting any stress symptoms (Table I-34). Trees that didn't exhibit any evidence that they had been subjected to poor planting practices were chosen for comparison. The dying and dead trees included: a nine-foot high blue spruce experiencing about ninety percent needle loss, a fifteen-foot high dead basswood tree and a fifteen-foot high dead white spruce. These dead and dying trees were compared with trees of the same species that appeared healthy. None of these trees were recent transplants to the park.

The data collected doesn't indicate that there is any direct relationship between the demise of the trees and the occurrence of landfill gas pollution in the soil of this park.

TABLE I-34. PERCENT COMPOSITION* OF SOIL GASES AT GOOD AND POOR GROWTH TREES

FREMONT PARK, IDAHO FALLS, IDAHO

	Good Tree Growth			Poor Tree Growth		
	Basswood	White Spruce	Blue Spruce	Basswood	White Spruce	Blue Spruce
Sample Depth	1'	1'	1'	1'	1'	1'
O_2	18½	-	8	7½	10	13
CO_2	2	-	8	35	10	3
Combustible Gas	0	0	0	3	0	0

*Average of 1-3 readings

Red Baron Alfalfa Field, Idaho Falls, Idaho

This landfill was completed in 1970 with ten to fifteen feet of municipal refuse. Alfalfa and rye grass were planted in 1976, but neither grew very well on the landfill. Settlement was observed to be severe over most of the site making cultivation difficult. The person responsible for farming the area felt that settlement was not the only problem. He noted that the alfalfa didn't grow well over the refuse.

The entire area being farmed was not on refuse. It was observed that the alfalfa planted off of the landfill was growing very well, reaching two to three feet in height. The alfalfa growing over the refuse was difficult to find. What was growing was mostly less than one foot in height. Weeds and grass were also growing better in the area off the refuse.

Comparisons were made of the soil atmospheres in the area over the refuse and that adjacent to the refuse (Table I-35). The soil appeared to be of better quality on the virgin land. The cover on the landfill also appeared to be a little shallow, only about a foot in some areas. Combustible gas and CO_2 concentrations were very high beneath the poor alfalfa growth and zero beneath good growth.

This site exemplifies the problems that can occur when trying to grow vegetation on a completed sanitary landfill. These problems include: settlement, poor soil conditions, difficulty in maintaining a satisfactory water balance, and pollution from landfill gases. It appears that a combination of these factors is probably responsible for the vegetation growth problems encountered on this former landfill.

TABLE I-35. PERCENT COMPOSITION* OF SOIL GASES AT GOOD AND POOR GROWTH ALFALFA

RED BARON ALFALFA FIELD, IDAHO FALLS, IDAHO

	Good Alfalfa Growth (Adjacent to landfill)	Poor Alfalfa Growth (On landfill)
Sample Depth	3'	3'
O_2	19½	5½
CO_2	0	34½
Combustible Gas	0	>50

*Average of 2-3 readings

Idaho Falls Child Development Center, Idaho Falls, Idaho

The Child Development Center is a special school for handicapped children. The school was constructed on a former sanitary landfill in 1971. The landfill operated from 1961 to 1964 depositing an average of about eight feet of municipal refuse. Settlement had damaged the building to the extent that a new roof had to be put on the structure.

Problems were reported with some of the trees that were planted when the site was landscaped in 1971-1972. Two blue spruces were said to be having problems growing. Since planting, the trees have grown very poorly exhibiting only sparse growth during most of the years.

An on-site inspection revealed that the most probable reason for the poor growth was a cement factory located across the street from the center. The needles were covered with cement dust to the extent that shaking the branches caused a cloud of dust to rise. Combustible gas readings near both trees were very low, ranging from zero to five percent at the three foot depth. Oxygen and carbon dioxide readings at the same depth were about normal, oxygen being around twenty percent and carbon dioxide 0.5 percent or less.

APPENDIX J

FIELD SURVEY DATA-MINERAL CONSTITUENTS AND SOIL CHARACTERISTICS

TABLE J-1. REGION Ar - TROPICAL, WET

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	782	800
Phosphorus	6	6
Potassium	134	130
Calcium	12,125	9,750
Ammonia-nitrogen	8	15
Nitrate-nitrogen	119	108
Organic matter	3.9	2.0
Moisture	-	-
ppm		
Iron	Tr.	Tr.
Manganese	6.25	8.75
Copper	0.90	0.65
Zinc	0.70	1.75
Boron	0.31	0.34
Iron/Manganese	-	-
Conductivity	3.7	4.2
pH	7.7	7.8
percent		
Sand	65.0	55.0
Silt	22.0	28.0
Clay	13.0	17.0

TABLE J-2. REGION BS - STEPPE

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	800	800
Phosphorus	2	3
Potassium	400	400
Calcium	7,200	7,800
Ammonia-nitrogen	2.4	1.0
Nitrate-nitrogen	20.0	17.0
Moisture	9.5	10.9
Organic Matter		
ppm		
Iron	2.4	-
Manganese	2.0	-
Copper	0.32	-
Zinc	0.60	-
Boron	1.95	2.0
Iron/Manganese	1.2	-
Conductivity	< 0.10	< 0.10
pH	8.5	8.4
percent		
Sand	40	44
Silt	34	36
Clay	26	20

TABLE J-3. REGION BW - ARID, DESERT

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	800	800	800	800
Phosphorus	106	176	152	227
Potassium	282	297	328	253
Calcium	1,662	1,700	1,683	1,850
Ammonia-nitrogen	11.8	69.3	17.3	17.0
Nitrate-nitrogen	2.8	12.3	3.7	2.0
Moisture	-	-	-	-
Organic Matter	1.6	2.1	1.3	1.5
ppm				
Iron	0.63	0.50	0.81	3.00
Manganese	8.3	12.7	33.7	37.0
Copper	0.25	0.42	0.38	0.25
Zinc	0.71	0.70	0.91	5.00
Boron	0.34	0.55	0.86	0.30
Iron/Manganese	0.08	0.39	0.02	0.09
Conductivity	0.34	0.99	0.79	0.44
pH	8.2	8.0	8.1	8.2
percent				
Sand	59.8	66.0	61.0	68.0
Silt	27.8	21.7	26.7	22.0
Clay	12.4	12.3	12.3	10.0

TABLE J-4. REGION Cf - SUBTROPICAL, HUMID

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	164	149	224	143
Phosphorus	63	60	9	9
Potassium	103	82	49	72
Calcium	827	1,248	411	310
Ammonia-nitrogen	8.5	4.5	3.9	10.0
Nitrate-nitrogen	13.7	11.3	3.6	10.0
Moisture	9.3	8.6	5.9	8.5
Organic Matter	1.9	2.1	0.8	1.2
ppm				
Iron	55.2	70.8	24.5	102.4
Manganese	19.5	23.2	11.4	25.5
Copper	0.68	1.16	0.76	1.00
Zinc	2.8	14.3	1.9	7.5
Boron	0.27	0.26	0.22	0.24
Iron/Manganese	2.83	3.05	2.15	4.02
Conductivity (Mols)	0.11	0.13	0.10	0.10
pH	5.6	6.0	5.8	5.8
percent				
Sand	66.7	76.3	66.7	66.7
Silt	18.3	12.6	13.3	14.7
Clay	15.0	11.0	20.0	18.7

TABLE J-5. REGION Cs - SUBTROPICAL, DRY SUMMERS

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	2,308	2,417
Phosphorus	1,074	1,130
Potassium	163	1,440
Calcium	3,275	2,508 *
Ammonia-nitrogen	4.8	9.0*
Nitrate-nitrogen	27.8	29.6
Moisture	5.1	7.6
Organic Matter	22.7	26.8 *
ppm		
Iron	2.4	4.3 *
Manganese	13.6	11.1
Copper	5.09	6.18
Zinc	5.22	7.72 *
Boron	-	-
Iron/Manganese	0.18	0.39
Conductivity	0.84	1.05
pH	7.3	7.0
percent		
Sand	37.3	39.3
Silt	29.3	28.6
Clay	33.3	32.0

*Significant difference at P = 0.05

TABLE J-6. REGION Dca - TEMPERATE, CONTINENTAL, HOT SUMMERS

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	125	186	51	39
Phosphorus	150	141	73	73
Potassium	80	104	72	86
Calcium	454	645	92	97
Ammonia-nitrogen	4.6	37.1	6.8	35.1
Nitrate-nitrogen	10.6	23.9	10.5	17.4
Moisture	6.3	9.7	8.4	10.8
Organic Matter	1.0	1.7	0.9	0.9
ppm				
Iron	58.2	104.3	57.5	186.4
Manganese	17.5	34.3	11.7	22.4
Copper	3.5	4.3	1.5	1.9
Zinc	5.5	6.3	2.2	2.1
Boron	0.36	0.23	0.18	0.13
Iron/Manganese	3.32	3.04	4.91	8.32
Conductivity (mohs)	0.10	0.18	0.12	0.12
pH	5.7	6.0	5.4	5.7
percent				
Sand	84.7	76.2	85.8	83.2
Silt	8.4	15.7	7.3	10.3
Clay	7.0	8.1	7.0	6.6

TABLE J-7. REGION Dcb - TEMPERATE, CONTINENTAL, COOL SUMMERS

Soil Constituent	Top Soil	
	No Gas	Gas
lb/acre		
Magnesium	209	196
Phosphorus	140	121
Potassium	112	150
Calcium	1,965	2,349
Ammonia-nitrogen	10.5	33.8 **
Nitrate-nitorgen	461.0	471.3
Moisture	14.8	15.8
Organic Matter	3.4	2.2
ppm		
Iron	0.4	62.4
Manganese	4.8	10.8
Copper	0.15	0.45
Zinc	0.80	7.00
Boron	-	0.17
Iron/Manganese	0.08	5.8
Conductivity (mohs)		
pH	5.7	5.9
percent		
Sand	78.3	81.1
Silt	13.1	11.3
Clay	8.6	7.8

** Significant difference at P = 0.01

TABLE J-8. REGION Do - TEMPERATE OCEANIC

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	800	800	800	800
Phosphorus	166	189	206	136
Potassium	154	114	181	175
Calcium	2,676	2,573	2,760	2,213
Ammonia-nitrogen	2.1	22.7 *	1.7	71.6
Nitrate-nitrogen	23.8	22.0	22.9	52.5
Moisture	8.2	11.4 *	23.7	11.7
Organic Matter	2.2	2.1	2.9	3.5
ppm				
Iron	116.7	162.9	116.0	247.7
Manganese	60.0	75.5	58.3	101.3
Copper	4.7	6.5 *	3.3	6.2
Zinc	10.4	17.0 *	3.1	6.5
Boron	0.34	0.57	0.32	0.34
Iron/Manganese	1.95	2.16	1.99	2.71
Conductivity (mohs)	0.12	0.26 *	0.19	0.28
pH	6.4	6.9	6.5	6.5
percent				
Sand	56.6	49.8	52.3	51.3
Silt	30	24.8		
Clay	16	14.8		

*Significant differences at P = 0.05

TABLE J-9. REGION H - HIGHLANDS

Soil Constituent	Top Soil		Sub Soil	
	No Gas	Gas	No Gas	Gas
lb/acre				
Magnesium	741	753	690	774
Phosphorus	5	8	10	204
Potassium	166	181	95	192
Calcium	8,789	7,608	9,424	8,420
Ammonia-nitrogen	1.9	0.9	1.0	2.0
Nitrate-nitrogen	14.2	17.6	10.0	48.0
Moisture	17.1	16.2	8.8	22.4
Organic Matter	1.5	2.7	2.9	6.5
ppm				
Iron	2.4	2.9	2.4	2.0
Manganese	3.6	13.9	8.4	12.0
Copper	0.28	0.20	0.30	0.40
Zinc	0.85	4.00	0.93	1.60
Boron	6.48	6.70	0.29	1.14
Iron/Manganese	0.67	0.21	0.29	0.17
Conductivity	0.10	0.20	0.11	0.15
pH	8.3	8.1	8.2	8.0
percent				
Sand	54	60.8	76	81
Silt	30	24.8	17	14
Clay	16	14.8	7	5

TABLE J-10. MEAN PERCENT (%) CHANGE IN CONTENT OF CONSTITUENTS OF SOILS FROM 9 CLIMATIC REGIONS AS SOIL PROCEEDED FROM NO-GAS TO HIGH GAS CONCENTRATIONS

Soil Constituent	Ar P.R.	Bs Utah	Bw Des.	Cf S.	Cs Cal.	Dca N.E.	Dcb M.A.	Do N.W.	H Mts.	Mean of 9 Regions
Mg *	± 2.3	± 0.0	± 0.0	- 9.2	+ 4.7	+ 48.8	- 6.2	± 0.0	+ 1.6	+ 4.6
P	- 0.0	± 50.0	+ 66.0	- 4.8	+ 5.2	- 6.0	- 13.6	+ 13.9	+ 37.5	+ 16.5
K	- 3.0	- 0.0	+ 5.3	- 20.4	- 11.7	+ 30.0	+ 33.9	- 26.0	+ 9.0	+ 1.9
Ca	- 19.6	+ 8.3	+ 2.3	+ 50.9	- 23.4	+ 42.1	+ 19.5	+ 3.8	- 13.4	- 7.8
NH_3-N	- 9.2	- 15.0	+ 33.9	- 17.5	+ 6.5	+125.5	+ 2.2	- 7.6	+ 23.9	+ 15.9
NO_3-N	+ 87.5	- 58.3	+487.3	- 47.1	+ 87.5	+672.9	+ 221.9	+800.0	- 52.6	+ 239.3
H_2O	-	+ 14.3	-	- 7.5	+ 49.0	+ 54.0	+ 6.8	- 12.7	+ 5.3	+ 15.6
O.M.	- 48.7	- 22.1	+ 31.3	+ 9.4	+ 18.1		- 35.2	- 9.3	+ 79.1	- 2.7
Fe	± 0.0	-	- 20.6	+ 28.3	+ 79.2	+ 79.2	+15500.0	+ 39.6	+ 28.0	+1967.0
Mn	+ 40.0	-	+ 53.0	+ 19.0	- 18.4	+ 96.0	+ 125.0	+ 25.8	+286.0	+ 78.3
Cu	- 27.8	-	+ 68.0	+ 70.5	+ 21.4	+ 22.9	+ 200.0	+ 38.3	- 28.0	+ 45.7
Zn	+150.0	-	- 1.4	+410.0	+ 47.9	+ 14.6	+ 785.0	+ 63.5	+370.0	+ 218.0
B	+ 9.7	+ 2.6	+ 61.8	- 3.7	-	- 36.1	-	+ 67.5	+ 3.4	+ 46.1
Fe/Mn	-	-	+387.5	+ 7.8	+ 116.7	- 8.4	+ 7150.0	+ 10.8	- 68.6	+1085.0
C.	+ 13.5	± 0.0	+191.2	+ 18.1	+ 25.0	+ 80.0	+ 66.7	+117.0	+100.0	+ 67.9
pH	+ 1.3	- 1.2	- 2.4	+ 7.2	- 4.3	+ 5.2	+ 3.5	+ 7.8	- 2.4	+ 1.6
Sand	- 15.4	+ 10.0	+ 10.4	+ 14.4	+ 5.4	- 10.0	+ 3.6	- 12.0	+ 12.6	+ 2.3
Silt	- 27.3	- 5.9	- 21.9	- 31.1	- 2.4	+ 86.9	- 13.7	+ 8.8	- 17.3	- 2.7
Clay	+ 30.8	- 23.0	- 0.8	- 26.7	- 3.9	+ 15.7	- 9.3	+ 10.5	- 7.5	- 1.6

*See page 129 for abbreviation key.

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TABLE J-10. (continued)

LIST OF ABBREVIATIONS*

Mg	--	Magnesium
P	--	Phosphorus
K	--	Potassium
Ca	--	Calcium
NH_3-N	--	Ammonia-nitrogen
NO_3-N	--	Nitrate-nitrogen
H_2O	--	Moisture
O.M.	--	Organic Matter
Fe	--	Iron
Mn	--	Manganese
Cu	--	Copper
Zn	--	Zinc
B	--	Boron
Fe/Mn	--	Iron/Manganese
C.	--	Conductivity

DISTRICT INFO
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CONTROLLED BURNING PROGRAM

Taking Care of Nature

Although fire can be threatening and destructive, it is an invaluable natural resource management tool that helps restore and maintain ecosystems.

Since 1975, the Forest Preserve District of DuPage County has used controlled burning to help restore native ecosystems and help clear way weedy, non-native vegetation.

The District manages more than 23,000 acres of open space at more than 50 different preserves. Picnic and camping areas, trails and parking lots make up only 10 percent of the District's land holdings. The remaining 90 percent is to remain in a natural state. To help restore and preserve the biological integrity of this land, the District uses fire as a key management tool on as much as 2,000 acres each year.

Natural History of Fire

Prior to 1830, when northern Illinois was tall grass prairie and savanna, fire was as much a part of the landscape as the naturally occurring forces of droughts, floods, blizzards, insect infestations and disease outbreaks.

Our native plants and animals are adapted to life with periodic burning. The main growing part of most prairie plants is in the roots. Some plants have roots up to 14 feet deep. Therefore, roots of native plants are not damaged by fire.

In pre-settlement times, fire occurred naturally, but was also started intentionally by man. Deliberately set fires were an important tool of native Americans who used fires to control flies and mosquitoes, to reduce ground cover for ease of travel and for hunting.

Today's man-made controlled fires simply continue a process that nature had started thousands of years ago on the Illinois prairie.

Why We're Burning

Fire is often perceived as a destructive and deadly force that scares people, but the Forest Preserve District views fire as a natural and necessary component of native ecosystems. While fire can be destructive under some circumstances, it enhances ecosystems when used properly.

When DuPage County was prairie, wetland and scattered open forests, naturally occurring wildfires frequently swept through this landscape and kept our prairies and woodlands open. Today, the District maintains this open landscape and controls non-native and invasive plant growth with controlled burns. The fires maintain these areas by killing or stunting invading woody and brushy vegetation, and recycles nutrients back into the soil while promoting the growth of native fire-tolerant plant species.

Because of the speed of the flames and the insulating properties of the soil, animals can avoid the fire. Directly behind the fire line, the ground is barely warm to the touch; and except for the charred plant remains, life goes on after the burn.

Fire benefits native plant growth by burning off dead accumulated plant material. Accumulation of this "litter" can lower the soil temperature and retard seed germination and plant growth. The material also tends to absorb rainfall, preventing it from reaching plant roots. By reintroducing fire into the landscape, we are able to restore some of the functional qualities of a true natural ecosystem.

Our plants and animals have lived harmoniously with fire over the centuries. Today, many native wildflowers are decreasing and non-native, invasive plants flourish as the county has become more populated. With the help of controlled burns as well as other natural resource management techniques, many native plant species are beginning to make a comeback.

Safety First

Any fire can be dangerous if not kept under control. Prior to a controlled burn, variables affecting fires are studied carefully. Wind conditions, humidity, temperature and the amount of moisture in plant material are all monitored by District ecologists and fire control crews who are trained to meet National Wildfire Coordinating and Group standards.

All fires are conducted with permits from the Illinois Environmental Protection Agency and local fire departments. The DuPage County Health Department, local police, DuPage County Sheriff, local and adjacent fire departments are all in close communication during the burning process. In addition, letters are sent to residents adjacent to designated burn sites. Replies to these letters assist the District in addressing health or other special concerns.

To Learn More

Visitors can get a closer look at the effects of fire on the natural environment by joining one of the District's naturalist-guided tours of a controlled burn in the spring or fall. A District representative can also visit groups and homeowner associations to further explain the reasons and benefits of the District's burn program. Watch for announcements of these fascinating programs in your local newspaper or in the District's quarterly publication, The DuPage Conservationist. If you have any questions or would like to schedule a speaker about controlled burns, please email or contact the Public Affairs Office at (630) 871-6406.

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Forest Sci., Vol. 27, No. 1, 1981, pp. 13–18

The Adaptability of 19 Woody Species in Vegetating a Former Sanitary Landfill

EDWARD F. GILMAN
IDA A. LEONE
FRANKLIN B. FLOWER

ABSTRACT. Ten replicates of 19 woody species were planted on a 10-year-old, completed sanitary landfill. An area of nearby old forest land served as a control. During the first 2 years after planting, blackgum (*Nyssa sylvatica* Marsh.), gingko (*Gingko biloba* L.), and Japanese black pine (*Pinus thunbergii* L.) tolerated the landfill conditions better than others. Soil oxygen, carbon dioxide, moisture content, bulk density, and temperature affected the survival of vegetation on the landfill. FOREST SCI. 27:13–18.

ADDITIONAL KEY WORDS. *Nyssa sylvatica*, blackgum, revegetation.

THE PRESSURES OF POPULATION EXPANSION and urbanization have prompted a reappraisal of anticipated uses for completed refuse landfill sites. In rural areas, intensifying land use has resulted in attempts to use completed landfills for parks, reforestation, and growing commercial crops. Numerous farmers, landscapers, and foresters have encountered mixed success in trying to establish agricultural crops, trees, and shrubs on landfills throughout the country (Flower and others 1978).

Various investigators have experienced difficulties in growing vegetation at completed sanitary landfill sites. Stunting of corn (*Zea mays* Sturtev.) and sweet potatoes (*Ipomoea batata* L.) became evident in areas adjacent to a New Jersey site where gases had migrated away from the landfill into the root zone of corn and sweet potato plants (Leone and others 1977). Death and poor growth of loblolly (*Pinus taeda* L.) and other pines planted on such sites in southern Alabama have also been attributed to the presence of fermentation gases in the soil environment (Flower and others 1978). Poor tree growth in these areas has also been associated with lack of soil moisture and increasing amounts of ammonia nitrogen, iron, manganese, zinc, and copper (Flower and others 1978).

The objectives of this investigation were to determine which species, if any, can maintain themselves in a landfill environment and to identify those factors which are most important in maintaining adequate growth of American basswood (*Tilia americana* L.; a reportedly sensitive species).

MATERIALS AND METHODS

Site Preparation.—The screening experiment was conducted on the Edgeboro Landfill, located on a marsh adjacent to the Raritan River in South River, New

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TABLE 1. Sum of Student's "t" (Σt) for nineteen species growing on the landfill and control plots in Edgebor, New Jersey.

Rank	Species		Growth on landfill as percent of control: Shoot	Stem area increase	Leaf bio-mass	Σ"t"
			Percent			
1	Blackgum	*Nyssa sylvatica*	81	118	75	2.66
2	Norway spruce	*Picea abies*	106	104	92	3.22
3	Ginkgo	*Ginkgo biloba*	100	59	97	4.95
4	Japanese black pine	*Pinus thunbergii*	73	96	75	6.59
5	Bayberry	*Myrica pennsylvanica*	84	70	115	6.62
6	Hybrid poplar (rooted cuttings)	*Populus* spp.	69	27	71	8.13
7	White pine	*Pinus strobus*	72	77	74	8.94
8	Pin oak	*Quercus palustris*	58	66	80	8.96*
9	Japanese yew	*Taxus cuspitata*	78	130	51	8.98
10	American basswood	*Tilia americana*	53	67	120	9.48*
11	American sycamore	*Platanus occidentalis*	103	63	68	10.66
12	Red maple	*Acer rubrum*	33	56	37	10.95*
13	Sweetgum	*Liquidambar styraciflua*	48	43	49	12.62*
14	Winged euonymus	*Euonymus alatus*	29	65	17	14.25*
15	Green ash	*Fraxinus pennsylvanica*	37	42	41	14.87*
16	Honeylocust	*Gleditsia triacanthus*	7	26	12	15.05*
17	Hybrid poplar (seedlings)	*Populus* spp.	15	0.2	12	20.33*
18	Weeping willow	*Salix babylonica*	13	0.1	33	21.20*
	Rhododendron	*Rhododendron 'Roseum Elegans'*	All plants died			

* Growth on the control was significantly greater ($P < 0.05$) than landfill plot for all three growth parameters.

Jersey. The deposited refuse was reported by the owner to be approximately 9 m deep. The general municipal refuse filling was completed at this location early in 1966. Later that year, 15–25 cm of soil were reportedly placed over the refuse as a final cover.

The experimental plot measured 22 m × 33 m (726 m^2) and the control plot, located approximately a quarter of a mile away on a formerly undisturbed woodland was 14 m × 33 m (462 m^2) in area. Thirty cm of sandy subsoil were spread over both the experimental and control areas followed by 15–25 cm of topsoil. Because there were 5–6 cm of original soil cover over the refuse prior to construction, this brought the total cover on the landfill to approximately 60 cm.

Selection of Species.—Nineteen woody species (Table 1) were selected for screening on the basis of their tolerance to low oxygen environments, ubiquity, seasalt tolerance, city tolerance, aesthetic landscaping purposes, or susceptibility to landfill gases.

Experimental Design.—Trees were planted in a nested design with two plots (landfill and control), five areas nested within each plot and two trees of each of the 19 species nested within each area. Thus, 10 replicates of each species were

planted on both plots. Tl
and principal componen

Soil Parameters.—In or
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on the landfill and m
weeks, beginning in Ma
lected with gas-tight syri
and methane in a Carle
atures at the 30 cm dept
same dates as were the
Beginning in mid-Marc
were made at 2-week int
control screening area. S
six areas in each plot.

Tree Parameters.—In th
which would become th
shoots of each tree wer
four longest shoots were
In order to measure th
were randomly selected
the following manner wh
from the past year's bud
Because evergreen trees
cuttings produced a true
randomly selected shoots
In March and Septemb
on each tree in both plot
at 30 cm from ground lev
30 cm from the base of t
sectional stem area and
tional stem area fr Ma
Four leaf weigh mpl
were selected at random
separate bag, dried for ap

Multiple Regression Anal
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of different levels of the s
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suited because it was rep
(Flower and others 1978)
showed that basswood tr
soil environments. The b
Smith 1966) was used to
variability in basswood
regression procedure wer

Results

Soil Parameters.—The m
ature (°C) on the landfill
moisture content (M.C.)
(Table 2). Bulk density (E

'ecies growing on the landfill

	Growth on landfill as percent of control		
hoot	Stem area increase	Leaf bio-mass	Σ''r''
	Percent		
81	118	75	2.66
106	104	92	3.22
100	59	97	4.95
73	96	75	6.59
84	70	115	6.62
69	27	71	8.13
72	77	74	8.94
58	66	80	8.96*
78	130	51	8.98
53	67	120	9.48*
103	63	68	10.66
33	56	37	10.95*
48	43	49	12.62*
29	65	17	14.25*
7	42	41	14.87*
	26	12	15.05*
15	0.2	12	20.33*
13	0.1	33	21.20*
	All plants died		

an landfill plot for all three growth

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ıpleted at this location early
tedly placed over the refuse

26 m²) and the control plot,
formerly undisturbed wood-
f sandy subsoil were spread
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sted design with two plots
d two trees of each of
licates of each species were

planted on both plots. The data were subjected to analysis of variance (Zar 1974) and principal components analysis (Harman 1967).

Soil Parameters.—In order to characterize the landfill cover-soil gaseous environment, gas samples were collected at the 30 cm depth from 42 buried samplers on the landfill and from six samplers on the control plot approximately every 2 weeks, beginning in March and ending in August 1977. Gas samples were collected with gas-tight syringes and analyzed for oxygen, carbon dioxide, nitrogen, and methane in a Carle Instrument Model 8500 gas chromatograph. Soil temperatures at the 30 cm depth were recorded at the same sampling points and on the same dates as were the gas measurements.

Beginning in mid-March 1977, soil moisture measurements (percent dry weight) were made at 2-week intervals on six samples from the landfill and four from the control screening area. Soil bulk density (g/cc) in the top 15 cm was measured at six areas in each plot.

Tree Parameters.—In the fall of 1976, the length of the leader shoot (if present) which would become the main trunk, and the lengths of the three next longest shoots of each tree were measured. When a leader shoot was not present, the four longest shoots were measured.

In order to measure the shoot length in 1977 for a particular plant, six shoots were randomly selected from each deciduous tree, shrub, and Japanese yew in the following manner when the plants stopped growing. Each shoot was measured from the past year's bud-scale scar to the tip of the current year's terminal bud. Because evergreen trees, other than Japanese yew, and hybrid poplar rooted cuttings produced a true leader shoot, this was measured in addition to five other randomly selected shoots from each plant.

In March and September 1977, stem diameter was measured at the same height on each tree in both plots with metal tree-calipers. Nine species were measured at 30 cm from ground level, the remaining ten species were measured from 10 to 30 cm from the base of the trunk. The stem diameters were converted to cross-sectional stem area and the data reported as the percent increase in cross-sectional stem area from March to September.

Four leaf weight samples were collected from each plant in 1977. Four shoots were selected at random, and all the leaves or needles from each placed in a separate bag, dried for approximately 24 hours at 65°C, and then weighed.

Multiple Regression Analysis.—Sixty-two American basswood trees (22 on control, 40 on landfill) were planted in the spring of 1976 in order to assess the effect of different levels of the soil parameters (carbon dioxide, oxygen, methane, temperature, moisture content, and bulk density) on tree growth. Basswood was suited because it was reported to be sensitive to high landfill gas concentrations (Flower and others 1978). A priori measurements of the various soil parameters showed that basswood trees were planted in areas representing a large range of soil environments. The backward elimination regression procedure (Draper and Smith 1966) was used to estimate those equations which best represented the variability in basswood growth measurements. The restrictions placed on the regression procedure were coefficients and F values significant at the 0.01 level.

Results

Soil Parameters.—The mean carbon dioxide (CO_2), methane (CH_4), and temperature (°C) on the landfill soil were significantly higher and the oxygen (O_2) and moisture content (M.C.) significantly lower ($P < 0.01$) than on the control plot (Table 2). Bulk density (B.D.) was similar for both plots.

TABLE 2. Mean carbon dioxide, oxygen, methane, temperature, moisture content, and bulk density on the landfill and control screen areas.[1]

Parameter	Landfill	Control
Carbon dioxide (percent)[2]	5.5 b	1.2 a
Oxygen (percent)[2]	17.8 a	19.7 b
Methane (percent)[2]	0.9 b	0.0 a
Temperature (°C)	19.0 b	17.9 a
Moisture content (percent dry wt.)	8.1 a	11.0 b
Bulk density (g/cc)	1.8 a	1.8 a

[1] Row means followed by different letters are significantly different with Student's "t" test ($P < 0.01$).

[2] Percent volume in gas sample.

Survival and Growth of Trees.—Significantly ($P = 0.07$) more trees died on the landfill (38) than on the control (24). All rhododendrons (20) died on both plots, 10 hybrid poplars (7, landfill; 3, control), 5 hybrid poplar cuttings on the control, 6 euonymus on the landfill, 3 blackgum on each plot, 6 willows on the landfill, and no more than 1 replicate of the remaining species died during the 2-year study.

No one growth parameter is best suited for comparing tree growth on the landfill with that on the control plot. Therefore, in order to rank the surviving species for tolerance to landfill conditions, results from two different statistical methods chosen to analyze the three growth parameters (i.e., shoot length, stem area changes, and leaf weight) were compared simultaneously. The first method consisted of calculating Student's "t" statistics for each parameter comparing the trees on the landfill with those on the control plot. The sums of the three "t" values for each species were calculated (Σ"t") and ranked in order from smallest to largest (Table 1).

The second method of analysis was the "principal components analysis technique." Since the standard deviation of each of the three growth parameters increased with an increase in the mean value, the analysis was performed on the natural logarithm of the original data. Factor scores were calculated for each species on the landfill and control plots using the regression method on the first factor (Harman 1967). The difference between control plot score and landfill score was calculated for each species and ranked in order from smallest to largest (Table 3). According to these data blackgum was the most tolerant and weeping willow the least tolerant. Shoot, stem, and leaf growth on the landfill plot as percent of control is also given for each species (Table 1).

Soil Parameters–Tree Growth Correlation.—The best equation describing basswood shoot growth was

$$\text{Shoot length} = 22.2 + 0.4\,(O_2) - 1.5\,(CO_2) - 0.2\,(\text{B.D.} \times CO_2). \qquad R^2 = 0.53$$

The best leaf weight equation:

$$\text{Leaf weight} = 37.7 - 0.2\,(\text{highest soil temperature}) - 10.1\,(\text{B.D.}) - 0.01\,(\text{M.C.} \times CO_2) + \frac{1.4}{(CO_2)^4}. \qquad R^2 = 0.63$$

The best stem area increase equation:

TABLE 3. Factor sour
and control plots in Ed

Rank	
1	Bla
2	Gir
3	Jap
4	Wh
5	No
6	Ba
7	Am
8	Pin
9	Hy
10	Jap
11	Gre
12	Wi
13	Am
14	Re
15	Sw
16	Ho
17	Hy
18	We
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** Growth on control was

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TABLE 3. Factor source differences for nineteen species growing on the landfill and control plots in Edgeboro, New Jersey.

Rank	Species	Factor score difference (control-landfill)
1	Blackgum	0.01
2	Ginkgo	0.07
3	Japanese black pine	0.27
4	White pine	0.31
5	Norway spruce	0.33
6	Bayberry	0.34
7	American sycamore	0.36
8	Pin oak	0.55
9	Hybrid poplar (rooted cuttings)	0.60
10	Japanese yew	0.79**
11	Green ash	0.83**
12	Winged euonymus	0.84**
13	American basswood	0.89**
14	Red maple	0.95**
15	Sweetgum	1.15**
16	Honeylocust	1.76**
17	Hybrid poplar	2.18**
18	Weeping willow	2.78**
	Rhododendron	All plants died

** Growth on control was significantly greater ($P < 0.01$) than landfill.

$$\text{Stem area increase} = 169.0 - 69.6\,(\text{B.D.}) - 2.1\,(\text{B.D.} \times CO_2) + \frac{9.6}{(CO_2)^4}. \qquad R^2 = 0.53$$

Discussion

Although gas (CO_2 and CH_4) concentrations in the experimental plot were not high enough to account for the death of many plants, landfill soil conditions were of a magnitude to detect the order of relative tolerance of the surviving trees (Table 1). This ranking resulted from a consideration of the three tree variables leaf biomass, shoot length (1976 and 1977), and stem area increase.

The ranking of species from best to poorest growth on the landfill compared to the control was similar for two methods of statistical analysis, i.e., Student's "t" test and factor analysis. Those species which grew significantly less on the landfill than on the control area according to the "t" test also made significantly less growth on the landfill according to "factor analysis" except for pin oak and Japanese yew.

Of the nine species whose growth on the landfill was not statistically different from growth on the control plot according to both methods of analysis, only two (blackgum and sycamore) in the "t" test column and three (blackgum, pin oak, and sycamore) in the factor analysis column have been reported (Hook and others 1972) to be able to withstand low oxygen tension in soil, one of the criteria for selecting the experimental species. Since the majority of these nine species were 91 cm or less in height when planted, and the majority of the nine species which made significantly less growth on the landfill than the control plot were 182 cm or taller when planted, further study is required to assess the effect of planting size on species adaptability to landfills. Possibly, the size of the tree at planting time, as well as the biological ability of species to withstand low soil oxygen, is important in selecting vegetation for completed sanitary landfill sites.

In order to estimate the relative effect of the soil variables on growth of trees on the landfill plot, multiple regression analysis was performed for American basswood because this species, unlike all the others, was replicated 62 times and, therefore, provided for the best assessment of the effect of the soil factors on tree growth. This species was also reported to be sensitive to high concentrations of landfill gas (CO_2 and CH_4) (Flower and others 1978). Regression coefficients were estimated using soil CO_2, O_2, and CH_4 concentrations, soil moisture content, soil bulk density, average soil temperature, highest soil temperature during the growing season, and a variety of interactions and reciprocals as independent variables. Soil bulk density, temperature, moisture content, O_2, and CO_2 (CO_2 as the reciprocal to the fourth power) explained a large portion of the variance ($R^2 = 0.53$ for stem area, 0.53 for shoot length, 0.63 for leaf weight) in the three growth parameters. In that $(1)/(CO_2)^4$ was significantly correlated with basswood growth, carbon dioxide appears to have affected growth at relatively low concentrations (1–10 percent). These results are in agreement with several authors who found that low levels of O_2 (Flower and others 1978) and moisture content (Gingrich and Russell 1957) and elevated levels of CO_2 (Flower and others 1978), soil temperature (Rattan 1974, Parks and Risher 1958, Shoulders and Ralston 1975) and bulk density (Gilman 1978, Hopkins and Patrick 1969) are associated with poor vegetation growth.

Conclusions

1. Blackgum, ginkgo, Japanese black pine, and Norway spruce tolerated landfill conditions better than others tested.
2. Soil carbon dioxide, methane, oxygen, moisture content, bulk density, and temperature were important soil factors controlling the growth of American basswood on the landfill plot on the Edgeboro sanitary landfill.

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CRITICAL FACTORS CONTROLLING VEGETATION GROWTH ON COMPLETED SANITARY LANDFILLS

by

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16. ABSTRACT

This study identifies some of the critical factors that affect tree and shrub growth on reclaimed sanitary landfill sites and determine which woody species are adaptable to the adverse growth conditions of such sites. Trees planted at the Edgeboro Landfill, East Brunswick, New Jersey produced less shoot and stem growth and shallower roots than trees on the adjacent control plot. Of 19 woody species planted 4 years ago on a 14-year-old landfill, black gum and Japanese black pine proved to be the most tolerant and green as ash and hybrid poplar the least tolerant to landfill conditions. Root systems of the more tolerant species proved to be shallower than those of the landfill intolerant species. Smaller planting stock (30-60 cm tall) appeared better suited for landfill planting than large trees (3-4 m tall). Balled and burlapped trees showed better growth on the landfill plot than bare-rooted material. Of five gas barrier systems tested, three proved effective: a soil trench underlaid by plastic sheeting over gravel and vented by means of vertical PVC pipes; a 0.9 m mound of soil underlaid with 30 cm of clay; and a 0.9 m soil-mound with no clay barrier.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollution discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, and provides a most vital communication link between the researcher and the user community.

In many areas of the country, completed sanitary landfills have been converted into parks, golf courses, and recreational areas, and woody trees and shrubs have been planted on these areas in order to make them attractive. The field experiments reported here were designed to identify the critical factors controlling vegetation growth on such sites. The study included determination of the adaptability of woody species to the adverse soil environment on a completed refuse landfill and a study of planting techniques for these areas.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This study identifies some of the critical factors that affect tree and shrub growth on reclaimed sanitary landfill sites and determine which woody species are adaptable to the adverse growth conditions of such sites. Trees planted at the Edgeboro Landfill, East Brunswick, New Jersey produced less shoot and stem growth and shallower roots than trees on the adjacent control plot. Of 19 woody species planted 4 years ago on a 14-year-old landfill, black gum and Japanese black pine proved to be the most tolerant and green ash and hybrid poplar the least tolerant to landfill conditions. Root systems of the more tolerant species proved to be shallower than those of the landfill intolerant species. Smaller planting stock (30-60 cm tall) appeared better suited for landfill planting than large trees (3-4 m tall). Balled and burlapped trees showed better growth on the landfill plot than bare-rooted material. Of five gas barrier systems tested, three proved effective: a soil trench underlaid by plastic sheeting over gravel and vented by means of vertical PVC pipes; a 0.9 m mound of soil underlaid with 30 cm of clay; and a 0.9 m soil-mound with no clay barrier.

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SECTION 1

INTRODUCTION

The sanitary landfill has been demonstrated to be the least expensive environmentally acceptable means of municipal waste disposal available to date, purportedly possessing the attribute of safety in addition to the relatively low cost. Though landfill sites may have originally been located at considerable distances from residential areas, rapid urban and suburban development in the United States has caused many once remote dumping grounds to be within developed areas. As such they provide an attractive source of much needed land for many purposes. Although conversion to recreational areas or other nonstructural usage has long been considered an acceptable end for completed landfill sites, the urgent need for space and for increased tax revenues has caused many municipalities to view completed landfills as acceptable for commercial use as well. In rural areas, intensifying land use has resulted in attempts to use completed landfills for growing commercial crops.

Regardless of the ultimate use of the landfill, certain serious disadvantages are inherent. Not the least of these are ecological upsets due to leaching of infiltrates and gases into groundwater, pollution of water supplies, production of toxic and explosive gas mixtures from anaerobic microbial decomposition of the organic matter present, and surface settlement. High ground temperatures have also been reported in the cover material of some completed refuse landfills.

Because abnormally high incidences of plant mortality were found on many landfills in New Jersey (Leone et al. 1977), it was desirable to determine if similar situations existed in other parts of the United States and to examine possible causes of and remedies for these vegetation growth problems. Reports from a nationwide mail survey funded by the USEPA, MERL, Solid and Hazardous Waste Division (Flower et al. 1978) determined that the scope of problems encountered when vegetating completed landfills was indeed of national magnitude. The landscaper, farmer and members of the general public would all benefit from successful vegetation projects such as parks, golf courses and recreational areas.

As urban population continues to grow, we can anticipate greater stimuli for converting former landfill sites into recreational areas and communities may be persuaded to convert these formerly unused lands into viable parks, golf courses and nature areas. Thus, it is vital to develop now the scientific knowledge required to perform these conversions. The goal of this project is to help develop these criteria through the accomplishment of the following tasks:

1. To determine the relative adaptability of nineteen woody species to landfill conditions.

2. To determine if rooting depth is related to the relative tolerance of trees to the landfill soil environment.

3. To determine if small planting stock can survive on completed landfills better than large specimens.

4. To determine if balled and burlapped plant material is better suited for landfill plantings than bare rooted material.

5. To determine the effects of irrigation on tree growth in landfill soil.

6. To determine if leaf tissue nutrient contents of trees in landfill soil differs from the nutrient contents of trees in non-landfill soil.

7. To determine the effects of high landfill gas (CO_2 and CH_4) concentrations on availability of soil nutrients.

8. To determine the feasibility of constructing barriers to the passage of toxic gases from the refuse into the root zone of gas sensitive species.

SECTION 2

CONCLUSIONS

SPECIES SELECTION

1. Woody species can be grown on completed sanitary refuse landfills.

2. The viability of woody vegetation in landfill conditions differs among species.

3. Rapidly growing trees appear to be more sensitive to landfill conditions than slow growers. However, since many of the rapidly growing trees (hybrid poplar cuttings, honey locust, red maple) produced more absolute growth on the landfill than the slow growers, rapid growers may be the more desirable species if one is not concerned about comparing growth on a landfill with the amount of growth normally produced on a non-landfill area.

4. Tree species planted as small seedlings appear better suited for landfill planting because they have the ability to quickly produce a shallow root system, whereas, larger sized saplings require more time to produce a shallow root system. A shallow root system may be more desirable because it allows roots to grow in a soil zone containing less landfill gas than the deeper soil zones close to the refuse.

5. Acid-loving plants (Japanese black pine, Norway spruce, black gum, bayberry) were more tolerant of landfill soil with a low pH (4.5) than of landfill soil with a higher pH (6.2).

6. Species tolerant to low oxygen environments (green ash, American sycamore, red maple, sweet gum, honey locust) did not tolerate landfill conditions as well as other species. Lack of sufficient soil moisture on the landfill soil was implicated as causing poor growth of these water loving species.

7. Species tolerance (based on comparisons of growth between landfill with growth on the control) differs according to shoot growth or stem area increase. Ginkgo, black gum, and Japanese yew were the most landfill tolerant species when shoot length was considered, whereas Japanese yew, white pine and Norway spruce were most tolerant when stem area increase was considered.

8. Low soil pH values (4.5) and high bulk densities (1.8 g/cc) may have predisposed several species (green ash, red maple, American sycamore) to

the adverse landfill soil environment.

9. An implication from these investigations is that if the study were to continue for several more years, some species which so far proved relatively intolerant to the landfill may eventually be regarded as tolerant because they may take longer to adapt to the landfill environment.

PREVENTING GAS MIGRATION INTO ROOT ZONES

1. Concentrations of carbon dioxide, oxygen and methane in the two mounds and gravel/plastic/vents trench were similar to those in the non-landfill control area indicating that these three gas barrier techniques are suitable for application in landfill vegetation projects.

2. American basswood trees growing in 0.9 m (36 in.) thick soil mounds (either unlined or lined with a 30 cm (12 in.) thick clay barrier) and in the gravel/plastic/vents trench generally produced more stem and shoot growth than trees in unmodified landfill soil. The other two trenches' gas-barrier systems did not promote better tree growth than the unmodified landfill areas.

3. American basswood in the gravel/plastic/vents trench and in the clay mound accumulated more of eight plant nutrients than trees in the unmodified landfill screening area.

EFFECTS OF SOIL FACTORS ON TREE GROWTH

1. Trees survived in landfill soil containing 3.9% CO_2, 0.4% methane and 18.8% O_2 but were killed in soil containing 22.8% CO_2, 12% CH_4 and 4.3% O_2. Trees cannot survive in soil containing these quantities of gas.

2. Irrigation significantly enhanced sugar maple growth in the landfill plot but not in the control.

3. When levels of CO_2, CH_4, O_2 and soil moisture in landfill soil change to levels not present in non-landfill soils, effects of these soil parameters on plant growth override the effects of the meteorological factors which normally affect tree growth.

4. Multiple regression analysis has shown that the soil environment on the landfill plot affected the ability of sugar maples to open and close their stomata. This may have caused some of the growth problems for trees on the landfill. However, on the control plot, meteorological factors appear to have affected stomatal changes in maple, whereas, the soil conditions had no effect.

5. Low soil moisture and high carbon dioxide (or low O_2) appear to have caused an increase in transpirational resistance and a decrease in growth of sugar maple on the landfill plot. This study presented evidence that changes in either one of these three factors alone while

the other is held constant resulted in significant changes ($P<.05$) in transpiration and growth of sugar maples.

6. Regression analysis showed that soil nitrate, soil oxygen and soil temperature are the most important factors in determining basswood growth. However, this study has presented evidence that soil oxygen concentration and temperature may have influenced the soil nitrate concentration and hence, tree growth.

EFFECTS OF SOIL ENVIRONMENT ON LEAF TISSUE NUTRIENT CONCENTRATIONS

1. American basswood leaf tissue nitrogen, potassium and manganese concentrations were significantly lower and magnesium and iron significantly higher in the area of highest carbon dioxide and lowest oxygen concentrations (clay/vents trench) than in all other areas.

2. Inhibition of tree growth by low oxygen and/or high carbon dioxide may have resulted in the inability of American basswood to accumulate manganese, thus the higher soil manganese content in areas of poor growth. However, reduction of manganese oxides due to low oxygen (4.3%) may also have contributed to the high manganese content in the clay/vents trench.

3. Levels of soil oxygen at 30 cm, bulk density and the highest temperature during the growing season were significantly (positively) correlated with leaf uptake of nitrogen, potassium, magnesium, calcium, manganese, copper and iron.

4. Efficiency of nitrogen, potassium, magnesium, calcium, iron and copper accumulation by American basswood was considerably reduced ($P<.01$) for trees growing in the clay/vents trench where the average soil carbon dioxide concentration was 22.8% and soil oxygen 4.3% compared to all other areas on the landfill and control plots where carbon dioxide averaged 7.0% or lower and oxygen was 16.3% or higher.

GROWTH OF BALLED AND BURLAPPED VS BARE-ROOTED STOCK

1. Balled and burlapped sugar maples adapted better than bare-rooted maples to the soil conditions in the landfill plot.

ROOT ADAPTATIONS IN LANDFILL SOIL

1. Root systems of the more tolerant species (Japanese black pine, Norway spruce) were much shallower than those of the intolerant species on the landfill and control plots.

2. The root adaptation mechanism of hybrid poplar associated with landfill tolerance appeared to be different from that of green ash. Deep poplar

roots (30 cm) grew toward the soil surface and proliferated there, whereas, ash roots at the same depth did not extend to the soil surface. Instead, a shallow root system was provided for by roots sprouting from the root collar, 2 cm below the soil surface. The roots proliferated at this depth resulting in a shallow root system.

3. Wind-toppled trees may become more common on landfill sites due to the lack of deep anchor roots. A deeper soil cover may promote a deeper root system and therefore, help prevent wind toppling.

4. The need for frequent irrigation on landfills becomes apparent since five of the six tree species were shown to produce a shallower root system on the landfill than on the control.

5. Multiple regression analysis showed that soil carbon dioxide and oxygen together accounted for 84% of the variability in total root length of American basswood.

6. Elevated levels of landfill soil carbon dioxide and methane in conjunction with low oxygen concentrations appear to be partially responsible for causing a decrease in total root length of American basswood and a reduction in the depth of maximum root penetration indicating a greater need for irrigation (at least 1"/wk) on completed landfills than non-landfill areas in order to maintain good tree growth.

7. At high landfill gas concentrations 30 cm below the soil surface (22.8% CO_2, 12.0% CH_4, 4.3% O_2), American basswood roots did not maintain good growth; however, at moderate concentrations 8.1% CO_2, 0.9% CH_4, 18.5% O_2), the roots had the ability to grow toward the soil surface and avoid the contaminated soil environment at the 30 cm depth. Therefore, basswood roots appear to tolerate moderate landfill gas contamination not so much by growing in the contaminated soil, but by avoiding the gases through the production of a shallow root system.

SECTION 3

RECOMMENDATIONS

SPECIES SELECTION

1. Since woody species differ in their adaptability to landfill soil, those charged with planting vegetation on completed landfills should avail themselves of current research on the adaptability of species to landfill conditions and avoid the use of nontolerant species.

2. Slow-growing trees appear to be better adapted to landfill conditions than rapid-growing trees.

3. Trees and shrubs planted as small specimens appear to be better adapted to landfill conditions than large specimens.

4. Species with a natural propensity for producing a shallow root are better suited for landfill vegetation projects than naturally deeper-rooted species.

5. Species reportedly tolerant to low oxygen environments will not grow well on landfills unless they are irrigated very thoroughly.

6. Balled and burlapped plant material appears to be better adapted than bare-rooted material to landfill soil.

PREVENTING GAS MIGRATION INTO ROOT ZONES

1. Landfill gases (primarily carbon dioxide and methane) must be kept away from the root system of trees and shrubs to promote good vegetation growth. Two methods proven effective are: a) a mound of soil (0.9 m) over existing cover and b) a lined and vented trench backfilled with suitable soil.

CRITICAL SOIL AMENDMENTS

1. Soil cover should be at least 0.6 m thick in order to promote good vegetation growth.

2. Landfill cover soil must be irrigated more frequently than non-landfill soil to promote good vegetation growth.

3. Soil nutrient and pH levels should be periodically checked to insure against dangerously high or low levels.

4. In order to prevent the cover soil from becoming highly compacted during the closing of the landfill, organic matter such as composted sewage sludge, leaves or peat moss might be mixed with the cover material before it is spread over the refuse.

FUTURE INVESTIGATIONS

1. This study presented evidence that carbon dioxide, methane and oxygen concentrations and moisture content in the landfill soil affect stomatal resistance of sugar maple. Further investigations should be conducted into the effects of carefully controlled levels of CO_2, CH_4 and O_2 and soil moisture on stomatal resistance to determine the degree of effect at various concentrations.

2. Additional controlled greenhouse studies are needed to ascertain the influence of soil gas levels on availability of soil nutrients and subsequent effects on plant growth.

3. Future screening studies should further test the hypothesis that rapidly growing trees are more sensitive to landfill soil pollution than slow growing trees.

4. Since rapidly growing trees draw more moisture from the soil and are thereby subjected to desiccation more quickly than are slow growers, the hypothesis that leaf antitranspirants slow the loss of moisture from the leaves and thereby enhance their landfill adaptability should be tested.

5. Further investigations of the effects of soil pH levels on species tolerance may be beneficial to our understanding of landfill vegetation growth.

6. Root investigations should be designed to determine if the adaptive capacity to produce a shallow root system in soil containing high concentrations of CO_2 and CH_4 differs among species.

7. Bare-rooted sugar maples appeared less suited than balled and burlapped maples for landfill plantings. Additional experiments should include a variety of species in order to determine if this relationship is universal or whether it is only characteristic of sugar maple.

8. Further in-depth studies of vegetation growth on former sanitary refuse landfills should include quantitative or qualitative investigations involving a number of other potentially toxic gaseous by-products of refuse decomposition such as ethylene, hydrogen sulfide and nitrous oxides.

9. Further experiments designed to test a variety of landfill gas-barrier

techniques should include replication of systems.

10. Additional shallow rooted species should be tested for their landfill tolerance.

11. Future investigations of plant growth on and adjacent to landfill sites should study the effects of long-term, low level gas contamination of the root zone on the incidence of plant disease and insect damage.

12. Procedures should be developed for spreading cover soil in a manner which does not cause high soil compaction.

13. Large and small specimens of many species should be planted on several different landfills in order to verify the recommendation for planting small trees on landfills.

14. Species screening experiments should include at least 20 replicates of each specie in each treatment.

15. The minimum soil depth required for grass and tree growth over landfills entirely covered with plastic sheeting should be determined. This information may be applied to refuse and hazardous waste landfill sites.

16. Leachate may be used for irrigation water in order to cut plant maintenance costs. However, leachates will vary with time and site and should be checked for undesirable characteristics.

SECTION 4

LITERATURE REVIEW

Many attempts to vegetate completed sanitary refuse landfills with trees and shrubs have been unsuccessful (Flower et al. 1978). The problems encountered during these projects have been identified (Flower et al. 1978). Gilman et al. (1980) have reported that tree and shrub species vary in tolerance to commonly occurring concentrations of landfill gases in the soil. Other detailed reports describing vegetation growth on landfills were not found in the literature.

EFFECT OF SOIL MOISTURE ON PLANT GROWTH

An important aspect of maintaining recently planted trees, shrubs and crops is assuring adequate soil moisture content in the root zone during the growing season. Rates of net photosynthesis decrease when plants are subjected to water stress (Troughton 1969). Direct effects of desiccation on the photosynthetic system (Troughton 1969) have been reported to cause shoot growth reductions in plum trees, leaf growth reduction in apple trees, fruit growth reduction in pear, and general growth reductions in many other fruit trees and field crops.

Fresh weight, dry weight and total root length of corn seedlings were reduced when either soil moisture or soil oxygen content was low (Gingrich and Russell 1957). Oxygen and moisture content interacted so that at high oxygen contents, growth was much reduced by low soil moisture; whereas at low oxygen contents, the growth difference between high and low soil moisture was insignificant (Gingrich and Russell 1957).

EFFECT OF ENVIRONMENTAL FACTORS ON LEAF TRANSPIRATION

Transpirational water loss is influenced by many plant factors such as leaf area, leaf anatomy, root:shoot ratio, stomatal frequency and control of stomatal aperature (Kramer 1933). Meteorological and soil parameters also have a marked effect on the stomatal changes in leaves. Meteorological and soil parameters on landfill areas are likely to be different than on non-land landfill areas.

Transpiration measurements differ from leaf to leaf within a given tree. The temperature of sunlit leaves may be 10-15°C above air temperature and of shaded leaves, 1-2°C above air temperature. On days following substantial rainfall, stomata on sunlit leaves remain open; however, several days later, stomatal resistance for sunlit leaves is often higher than that of shaded leaves (Butler 1977).

Experiments conducted with four oak species and sugar maple showed that when air temperature was increased from 20-35°C, stomata opened and tranpiration increased (Wueuscher and Kozlowski 1971). In cocklebur (Xanthium pennsylvanicum) photosynthetic removal of carbon dioxide at increased light intensities was responsible for the opening of stomata (Mansfield and Heath 1961). Increasing the temperature during the night caused the stomata to open to a point comparable in magnitude to that in light of moderate intensity (Mansfield 1965). Meidner and Heath (1959) described two opposing effects of increasing air temperature on onion (Allium cepa) stomata: a closing effect which was shown to be due to accumulation of carbon dioxide in the leaf tissue and an opening effect when such accumulation was prevented.

A comparison was made by Davies and Kozlowski (1974) between stomatal opening and closing in response to changes in humidity. Seedlings of white ash and sugar maple were subjected to relative humidity changes from 20-80 percent at two light intensities (6,500 lux and 32,000 lux). Increases in humidity caused stomatal opening; decreases caused stomatal closure, as is normal for most plants. However, stomata were less affected by humidity changes at high than at low light intensities. These same phenomena have been reported for other species (Leyer and Stocker 1965). Experiments by Schulze et al. (1972) with three plant species differing completely in their ecological demands yielded basically the same results i.e. increased humidity opens stomata and lowering humidity closes stomata. Interactions between humidity and temperature effects on leaf resistance may partially explain conflicts in the literature concerning temperature effects on stomata as suggested by Schulze et al. (1972). One study indicates that stomata of orange may close when temperature is increased while relative humidity decreases; but that increasing temperature between 20-40°C may cause stomata of orange to open slightly, provided humidity remains constant (Hall et al. 1975). There has been no published literature on the effects of soil temperature on stomatal opening changes, and ultimately on growth for plants growing on landfill soils.

Soil moisture content was also found to interact with humidity in regard to stomatal resistance. Unirrigated Hammada scoparia plants were found to respond more quickly and to a greater degree to changes in air humidity than were irrigated plots (Schulze et al. 1972). In bean plants, stomatal conductance decreased with decreased air humidity; however, the reduction was greater at higher soil moisture contents (Moldau and Syber 1976).

Davies et al. (1969) report that increasing wind speed over a leaf surface causes variable responses in different plants. Transpiration over a 24-hour period was increased by wind in ash, decreased in maple, and unaffected in pine. These differences were reflected in stomatal control i.e. whereas maple stomata closed rapidly when exposed to wind, those of ash did not.

EFFECTS OF SOIL CONDITIONS ON NUTRIENT UPTAKE

Levels of soil nutrients available to plant roots may be affected by the soil atmosphere in sanitary landfill soil (Gilman 1978). Previous studies suggest that changes taking place in flooded soil generally parallel changes in landfill soil (Flower et al. 1978). Several soil elements e.g. manganese, iron, and sulfur become more available in flooded soil due to low oxygen levels (Ponnamperuma 1964). Higher available levels of these elements in the soil are often accompanied by their increased uptake by plant roots.

It has been shown since the early 1900's that plants grown in solution culture require both air and minerals in order to achieve adequate growth (Erickson 1946). There is a good deal of variability among plants in tolerance to low oxygen or high carbon dioxide concentrations and high soil temperatures in the root zone (Flower et al. 1978).

Soil compaction can also dramatically affect the response of plants to the soil environment by decreasing total pore space and by reducing the size of the pores. Veihmeyer and Hendrickson (1946a) found that the roots of sunflowers in the laboratory and grape vines in the field both penetrated a loam soil to the depth at which the bulk density reached 1.8 g/cm^3, but would not penetrate any further where bulk density was higher. In a later paper, Veihmeyer and Hendrickson (1946b) reported that roots would not penetrate a loamy soil with bulk density above 1.9 g/cm^3, whereas 1.6 to 1.7 g/cm^3 was the limiting value in clay soil. They attributed the failure of roots to penetrate soil with a bulk density above the critical (limiting) value to the size of the pores and not to the lack of oxygen, pointing out that roots can penetrate water-saturated noncompacted soils. In a compacted soil, roots of sugar cane were restricted to the top few inches; whereas in well structured soil, roots penetrated throughout the tilled horizon (Trouse and Hamber 1961). A bulk density of 1.12 g/cm^3 slightly reduced root penetration in sugar cane, a value of 1.36 g/cm^3 reduced root growth and caused rootlet distortions, and a value of 1.46 g/cm^3 seriously reduced root penetration. Sugar cane roots completely avoided growing into soils whose bulk densities exceeded about 1.52 g/cm^3 (Trouse and Hamber 1961). Parker and Jenny (1945) found that water infiltration of soil decreased as bulk densities increased, resulting in erosion and soil with a lower moisture content than that of a less compact soil.

The accumulation by plants of a number of nutrients is reportedly affected by poor soil aeration. Several authors have shown that potassium is the first mineral to decrease in leaf tissue under poor aeration (Broadbent and Stojanovic 1952; Hoagland and Broyer 1935; Lety et al. 1966). A suppressed soil oxygen supply to the roots of avacodo significantly decreased the leaf concentration of N, P, K, Ca, Mg and B (Labanauskas et al. 1968). Leyshon and Sheard (1974) found that low oxygen levels decrease N, P and K concentrations by 51, 61 and 58% respectively, and may account for reduced barley growth. Shoulders and Ralston (1975) reported that low oxygen levels attenuated the uptake of P, K, Ca and Mg in slash pine, but increased NO_3 uptake. In these studies high soil levels of methane, nitrogen, and carbon dioxide reduced phosphorus uptake to a greater extent than that of nitrogen and potassium. Phosphorus uptake was significantly reduced in leaves but increased in roots, suggesting an immobilization mechanism in roots. Since high soil carbon dioxide, nitrogen, and methane affected phosphorus uptake similarly in contrast to air, a lack of oxygen was suspected as the causal mechanism - not gaseous toxicity (Meiklejohn 1954; Niranjan and Mikleisen 1977).

Hammond et al. (1955) observed an interaction between oxygen and carbon dioxide when 5% carbon dioxide combined with 1% oxygen applied to corn roots resulted in the same potassium deficiency as treatment with 20% carbon dioxide and 20% oxygen. They concluded that soils associated with plants exhibiting potassium deficiencies, even though adequately supplied with potassium, often consist of heavy silt to silt-clay, have poor structure, are compacted by weather or are high in calcium.

Low soil oxygen alone or in conjunction with flooded soil has been associated with an increase in trace element contents (e.g. iron and sodium) in avacodo seedlings (Labanauskas et al. 1968). Increased soluble levels of iron in some reduced soils have been reported to result in iron toxicity to crops (Howeler 1973; Ponnamperuma 1955). The adverse effects on plants of high levels of available iron in reduced soils may result from direct toxicity; however, several reports in recent years suggest that the mechanism of iron toxicity may involve indirect effects of excess iron. Howeler (1973) postulated that excess soluble iron in flooded oxisols in Columbia may coat roots with an iron oxide barrier layer, thereby reducing nutrient transport from the soil into the plant. As a result, rice plants were assumed to be deficient in phosphorus, potassium, calcium, and magnesium as a result of iron accumulation in the root zone. Jones (1975) also suggested that reduced phosphorus uptake by some dune slack grass species may be attributed to phosphorus immobilization at the root surface due to the high level of iron associated with roots in waterlogged soils.

Waterlogged soils and sediments high in organic carbon content may become strongly reduced, resulting in sulfate reduction and sulfide accumulation. The detrimental effect of hydrogen sulfide on root function and plant growth is well established in the literature (Hollis 1967; Ponnamperuma 1955; Vamos 1958). Several studies on the mechanisms of toxicity have indicated that the presence of hydrogen sulfide may also limit nutrient uptake (Hollis et al. 1975; Joshi et al. 1975). Ford (1965) Mitsui and Kumayawa (1964) suggested that the mechanism involved is an adverse effect of hydrogen sulfide on enzymatic reactions.

Few investigators have studied the effect of soil temperature on nutrient accumulation. Rattan (1974) reported a decrease in uptake by corn of nitrogen, potassium and zinc and in translocation of nitrogen at high soil temperatures. The requirement for calcium in wheat was found to increase with an increase in soil temperature from 20°C to 30°C (Burstrom 1956). Neilson (1971) also observed a greater plant response to the addition of calcium at higher soil temperatures (25-30°C) than at lower temperatures (15-20°C). Tissue content of N, P, K, Ca and Mg in corn, bromegrass and potato increased with increasing temperatures from 5°C to 19.5°C, above which total tissue nutrient content leveled off or decreased. During this investigation (Neilson 1971), high nutrient uptake at temperatures favorable for plant growth was greatly dependent on the amount of nutrients added to the soil medium. For example, total uptake of phosphorus by corn at 27°C without added phosphorus fertilizer was only 10% of that accumulated at this temperature with an N, P, K fertilizer treatment. A favorable temperature did not compensate greatly for lack of nutrients, nor did addition of nutrients offset the effect of unfavorable temperature.

EFFECTS OF SOIL CONDITIONS ON ROOT GROWTH

Information is available on the restriction of root growth by low soil oxygen supply (Leonard and Pinkard 1946), high carbon dioxide supply (Geisler 1963; Chang and Loomis 1945), mechanical impedence due to high soil compaction (Hopkins and Patrick 1969) and interactions among these parameters (Hopkins and Patrick 1969). These conditions often occur in landfill soil environments; however, studies describing root distribution in such areas are wanting. The studies presented herein characterize root systems growing in a sanitary landfill soil environment.

Most of the available information on the extent and concentration of forest tree root systems has been obtained by excavation and mapping exposed roots of seedlings or mature trees (Dean 1956; Pavlychenko 1937), and most of this work has been largely confined to species of pine, with relatively little attention to broadleaved deciduous trees. Such studies have largely dealt with three categories of root behavior: depth of penetration, tendency to concentrate, and lateral spread.

Lailtakari (1929) observed Scotch pine to be more shallowrooted on sandy soils than on loamy soils. Kaleda (1949) found that in individuals of this species growing in sandy soils, about 87% of the horizontal root system was located in the upper 8 inches. However, some secondary roots that originated from the taproot deep in the soil rose systematically to the surface (Lailtakari 1929). A similar situation was reported for bur oak by Weaver and Kramer (1933). The horizontal root distribution of white pine (Lutz et al. 1937) was found to be different in various soil horizons but the greatest development was always found in the upper (A horizon) soil layers.

One of the most intensively studies conifers in the United States with respect to root development is longleaf pine. Hodgkins (1977) reported that lateral root length and spread of this species increased with improved competitive position of the tree and with age up to maturity. Heyward (1933) observed that lateral roots of longleaf pine grew at a uniform depth throughout their length. Holch (1931) explained the pattern of heavy taproot plus prominent long laterals radiating at shallow depths from the taproot, described by (Lenhart (1934) and Wahlenburg (1946), as a characteristic of species adapted to drier sites.

Holch (1931) reported that the spread of roots of five species of deciduous trees greatly exceeded the height and spread of the tops. Kramer and Weaver (1933) observed that most of the major laterals of bur oak originated in the upper 2 feet of soil. The results of a study investigating morphological root characteristics of nine selected northeastern hardwoods

(Stout 1956) revealed that the mean depth of the laterals was between 10 and 18 inches for four of the species while that of the other five species averaged less than 10 inches.

While investigating oak growth in the Arizona chaparral, Davis and Pace (1977) found live roots down to a depth of 21 feet.

Results of the above investigations show that many tree species develop relatively shallow root systems, although additional taproots extending down several feet are often found originating from laterals.

Studies on the tolerance of plants to waterlogging, many of which have been reviewed by Grable (1966), Gill (1970) and Rowe and Beardsell (1973), have been concerned with responses of root and shoot to lack of oxygen and to injurious chemical substances produced in the soil and in plant tissues, as well as with mechanisms of tolerance in certain species.

Periodic or permanent waterlogging is an important characteristic of many forest sites where Sitka spruce (Picea sitchensis) and lodgepole pine (Pinus contorta) are the species most frequently grown. On such sites, soil oxygen can decrease abruptly a short distance below the surface (Armstrong et al. 1976) and consequent injury to the root system results in shallow-rooted unstable crops. Field studies on Sitka spruce (Lees 1972) and lodgepole pine (Baggie 1972) growing on peat soils show that root development of both species is affected by waterlogging. Actively growing greenhouse-rooted lodgepole pine cuttings were more tolerant to waterlogging than spruce, when assessed in terms of the survival of both the tip and basal region of the root. By contrast, dormant roots of both species were so tolerant to waterlogging (28 days) that the tips remained alive and rapid regrowth took place after the soil was drained (Coutts and Philipson 1978).

During further investigations Coutts and Philipson (1978a) found that lodgepole pine roots penetrated to depths of 20 cm at 10°C in soil devoid of oxygen, whereas Sitka spruce made only shallow growth into the watertable. The results suggested that the deeper penetration of waterlogged soil by lodgepole pine than by spruce is due to internal oxygen transport in the pine roots. Philipson and Coutts (1978b) later showed that the pine had a greater capacity for oxygen transport to the flood-intolerant spruce.

Studies concerning the morphologic adaptations necessary for plants to withstand periods of anaerobiosis cite two types of modifications: i.e. increased branching of roots and the formation of adventitious roots. Geisler (1965) found that a reduction in the oxygen supply lead to a higher number of lateral roots per unit of root length and an enhancement in the density of the root system. As a consequence of increased root numbers, the area for active ion absorption located close to the root tips is increased (Brouwer 1965).

Kramer (1951) postulated that the formation of shallow adventitious roots is an important modification for plants to survive oxygen depletion. The adventitious roots of some species contain more air space than the primary root systems, allowing oxygen to diffuse more freely down to the primary root system (Luxmoore 1969).

Alberda (1953) observed that in rice, a mat of fine dense roots was formed at the surface of the water at the end of the tillering period. He suggested, and Voloras and Letey (1966) later demonstrated, that adventitious roots formed during aerobic conditions did not transport oxygen to the primary roots as effectively as did adventitious roots developed during anaerobiosis. Several deciduous tree species planted on mine spoil soil formed flat root systems, with virtually all root development in the surface and near surface layers (Zdzislaw and Greszta 1969). The authors imply that chemical properties of the soil can account for the development of shallow roots.

Research efforts aimed at establishing vegetation on completed sanitary landfills, let alone characterization of root systems growing in such environments, are limited. A study evaluating species adaptability to a landfill in California (1974) reports that root systems of the trees are shallow and lacking in strength. Reinhardt (1973) writes in the final report describing a refuse-milling project in Madison, Wisconsin, that when root systems are limited in extent and function by deficient moisture, deficient oxygen or high soil strength; fertilizers are apparently not utilized by the trees in sufficient quantities to cause measurable growth changes. Since neither of the above studies contain quantitative data, interpretation of these statements is difficult.

In summarizing the results of an evaluation of 19 species to landfill environments, Gilman (1978) observed that woody plants growing in a landfill soil develop a greater proportion of their root system in the top 13 cm than the same species growing on a nearby non-landfill area. The need for a more thorough root distribution characterization in trees growing in landfill soil is clearly apparent in that the ability of a species to tolerate the landfill environment appears to be partially related to its ability to establish a shallow fibrous root system.

SECTION 5

METHODS AND MATERIALS

TREE PLANTING

Species Screening Experiment

During the spring of 1976, 10 replicates of 19 woody species were planted on both the completed 14-year old Edgeboro sanitary refuse landfill located in East Brunswick, New Jersey and on a nearby non-refuse control area (Table 1). The species were evaluated during the 1976 and 1977 growing seasons for their ability to tolerate soil conditions present in the landfill soil (Gilman 1978). Data presented in this report were collected from the trees during 1978 and 1979 and compiled with portions of data collected during 1976 and 1977.

Gas-Barrier Techniques

During the spring of 1976, American basswood (*Tilia americana*) and Japanese Yew (*Taxus cuspidada*) were planted in replicates of six in each of seven gas-barrier areas: three trenches and two mounds on the landfill plot and one trench and one mound on the control plot (Gilman 1978; Leone et al. 1979). Following the removal of the basswoods and yew in the trench areas in the spring of 1978, two-year old black gum (*Nyssa sylvatica*), honey locust (*Gleditsia triacanthos*) and pin oak (*Quercus palustris*) seedlings were planted in replicates of six in the three landfill trenches and control trench and in the landfill and control unmodified areas.

TABLE 1. SPECIES SELECTED FOR VEGETATION GROWTH EXPERIMENT AT EDGEBORO LANDFILL

Latin name	Common name
Acer rubrum	Red maple
Euonymus alatus	Euonymus
Fraxinus lanceolata	Green ash
Ginkgo	Ginkgo
Gleditsia triancanthos	Honey locust
Liquidambar styraciflua	Sweet gum
Myrica pensylvanica	Bayberry
Nyssa sylvatica	Black gum

(continued)

TABLE 1. (continued)

Latin name	Common name
Picea excelsa	Norway spruce
Populus spp.	Hybrid poplar (saplings)
Populus spp.	Hybrid poplar (from rooted cuttings)
Plantanus occidentalis	American sycamore
Pinus strobus	White pine
Pinus thunbergi	Black pine
Quercus palustris	Pin oak
Rhododendron hyb. 'Roseum Elegans'	Rhododendron
Salix babylonica	Weeping willow
Tilia americana	American basswood
Taxus cuspidata var. capitata	Japanese yew

Irrigation Effects on Tree Growth

To investigate the effects of irrigation on survivability of trees in landfills, thirty 2-year old sugar maple (*Acer saccharum*) seedlings spaced 1 m (39 in.) apart were planted in the spring of 1978 in two separate areas on both the landfill and control plots. One group of 30 trees on each plot was periodically irrigated during the 1978 and 1979 growing seasons according to the schedule presented in the irrigation section of this report. The other area was not irrigated and is referred to as the non-irrigated area in this report.

Effect of Size of Planting Stock on Species Tolerance to Landfills

To determine if the size of planting stock influences the ability of trees to survive in a landfill environment five 6-7 year-old, 2.5 m (98-in. tall) sugar maple saplings; ten 2-year-old 0.5 m (20-in. tall) sugar maple seedlings and ten 2-year-old green ash (*Fraxinus lanceolata*) 0.5 m (20-in. tall); were planted in the spring of 1978 on the landfill and control screening areas. Growth of the larger sized green ash planted in 1976 was compared with growth of the smaller ash trees to assess the effect of planting size on landfill survivability and growth.

Type of Planting Stock in Relation to Landfill Tolerance

In order to determine which type of planting stock is best suited for completed landfills five balled-and-burlapped (B&B) 2-3 m (79-118 in. tall), and five bare-rooted 2-3 m (79-118 in. tall) sugar maples were planted on the landfill and control screening areas in the spring of 1978.

CULTURAL METHODS

Fertilizing

In October 1977 and 1978, soil nutrient analyses for both plots indicated low nitrogen, phosphorus and potassium levels. In order to raise these levels to an adequate range, on April 21-24, 1978 and April 25-26, 1979, 1.13 Kg (2.5 lbs) of 10-6-4 granular fertilizer were spread around each tree on all plots with a standard granular fertilizer spreader.

Liming

In order to raise the pH from approximately 5.0 to between 6.0 and 6.5, 0.57 Kg (1.25 lbs) of pulverized dolomitic limestone were applied to the soil around each tree on both plots by means of a walk-behind spreader on April 29, 1978. Since the pH did not rise to the desired level, application rates were recalculated and 1.8 Kg of additional limestone were applied on April 30, 1979. The pH was brought to the 6.2 level.

Irrigation

The rainfall in New Brunswick in the early spring of 1978 was sufficient to maintain the soil at a moisture level adequate for tree growth; but by the middle of May, the soil moisture had reached a level low enough to warrant irrigation. Soil moisture was tested by squeeze method. When water dripped from the soil when squeezed, it was classified as wet; when no water came out but the soil stayed together in a clump, the soil was moist; when the soil crumbled after squeezing, the soil was considered dry and the soil was irrigated. Approximately 39 L (10 gallons) of water were applied to all trees with a center-pivot irrigator during each irrigation period. Trees were irrigated four times during 1978.

Rainfall during the 1979 growing season was sufficient to warrant irrigation only twice during the summer. Approximately 39 L (10 gallons) of water were applied to each tree during irrigation periods.

During the investigation of the effects of irrigation on sugar maple growth, one group of 30 plants was irrigated in the landfill and control plots during the summer (1978 and 1979) so that the amount of water from rainfall and irrigation totaled approximately 2.5 cm (1 in.) per week. Plants were not irrigated if more than 2.5 cm (1 in.) of rain had fallen during a given week. Another group of 30 maples on each plot was not irrigated.

Pest Control

On May 7, 1978, pin oak, American basswood, weeping willow and hybrid poplar were sprayed with liquid Sevin for the control of tent caterpillars and canker worms which were present on some trees. A second spray was applied on May 23, 1978 for the same insect pests.

Red-headed pine saw flies were found on several Japanese black pine trees on the landfill plot during the week of August 7, 1978. The black pines on both plots were sprayed with Malathion on August 10 to control this pest.

Rodent Control

In order to protect the bark and cambium of young seedlings from rabbit damage, 0.5 m (20 in.) high chicken wire was placed around areas which contained seedlings susceptible to rabbit injury.

Weed Control

During the 1978 growing season, grass and weeds were periodically cut with a power mower and weeds were pulled from the area immediately surrounding each tree trunk.

Weed growth in 1979 was chemically controlled. In April, three-eighths (3/8) cup of Roundup and one-half ($\frac{1}{2}$) cup of Princep were diluted with water to make three gallons of solution. This mixture was applied to the soil until the ground was thoroughly wet. This procedure was repeated in June.

SAMPLING METHODS

Soil Measurements

Soil gas content, temperature, bulk density, moisture content and nutrient concentrations were measured throughout the 1978 and 1979 growing seasons as described by Gilman (1978).

Tree Measurements

Shoot length and stem area (Table 2) are measured on each tree in the fall of 1978 and 1979 and root biomass was measured on each tree during the 1977 growing season. These procedures were presented in an earlier report, Gilman (1978) and Leone et al, (1979).

TABLE 2. DISTANCE FROM THE SOIL SURFACE AT WHICH STEM INCREMENT WAS MEASURED

Species		Distance from soil
Latin name	Common name	(cm)
Acer rubrum	Red maple	30
Euonymus alatus	Winged-euonymus	5
Fraxinus lanceolata	Green ash	30
Ginkgo biloba	Ginkgo	30
Gleditsia triacanthos	Honey locust	30
Liquidambar styraciflua	Sweet gum	8
Myrica pennsylvanica	Bayberry	3
Nyssa sylvatica	Black gum	8
Poplus sp.	Hybrid poplar (saplings)	30
Poplus sp. m	Hybrid poplar (rooted cuttings)	5

(continued)

TABLE 2. (continued)

Species		Distance from soil (cm)
Latin name	Common name	
Picea glauca	Norway spruce	3
Platanus occidentalis	American sycamore	30
Pinus strobus	White pine	5
Pinus thunbergi	Japanese black pine	5
Quercus palustris	Pin oak	30
Rhododendron elegans	Rhododendron	3
Salix babylonica	Weeping willow	30
Tilia americana	American basswood	30
Taxus cuspidata capitata	Japanese yew	3

Leaf Weight--

In order to measure the amount of leaf biomass produced by each American basswood on the seven gas-barrier areas and the landfill and control screening areas, four shoots were selected at random from each plant, one in each of the cardinal compass points (N, S, E, and W). From each of these four shoots, all the leaves were collected from last year's bud scale scar to this year's terminal bud and placed in four separate bags. The leaves were dried for approximately twenty-four hours at 65°C and weighed.

In order to measure average leaf weight of the sugar maples in the irrigation experiment, two leaves, i.e. about 10% of the total number, were randomly chosen from each tree. Leaves were dried for approximately 24 hours at 65°C in a forced air drying oven and weighed to the nearest milligram. Total leaf biomass produced by each tree was calculated by multiplying average leaf weight by the average number of nodes/shoot.

Tissue Nutrient Content--

On August 7, 1977, American basswood leaf tissue samples for elemental analysis were collected in the following manner: five shoots were randomly selected from each tree in each gas-barrier technique and landfill and control screening areas. Four leaves were collected from each shoot for a total of 20 leaves/tree. The leaves were dried for 24 hours at 40°C in a forced air drying oven, and ground through a 40 mesh screen. Chemical analysis of this tissue was determined according to methods presented in the Chemical Analysis portion of this report.

Transpiration Rate--

The physiological condition of the sugar maple seedlings planted for the irrigation experiments was monitored by measuring the rate of transpiration from a given area of leaf surface with a Lambda Instruments Diffusion Resistance Meter. Transpiration studies were designed for two purposes: the first was to investigate the transpirational strategy of sugar maple seedlings in the irrigated and non-irrigated areas on the landfill plot throughout an entire day and the second was to study the transpirational strategy over a period of days on the landfill and control plots.

In the first experiment, five maples were randomly selected from the irrigated area where carbon dioxide averaged 2.3% and methane 0%; five from the non-irrigated area which contained 2.8% carbon dioxide and no methane; and five from another area in the non-irrigated area where carbon dioxide content was highest (7.8%) and methane was zero. Sugar maple was selected because of its reported sensitivity to landfills and flooding conditions (Leone et al. 1979). Diffusive resistance measurements were obtained from two leaves per tree starting at 8:30 a.m. and continuing at one hour intervals through the day until 8:30 p.m.

I the second experiment, ten trees were randomly selected from the irrigated and non-irrigated areas on both plots. Diffusive resistance was measured daily on two leaves per tree between 10 and 12 a.m. starting on August 9, and continuing through August 23, 197'.

Meteorologic Measurements

Air temperature and humidity data were obtained from the Rutgers University Meteorology Department for each hour during the day corresponding with the time of transpiration measurement. Wind speed and light intensity measurements were unobtainable because the weather station was being relocated during August 1978. Total wind movement (in miles per day) measurements were obtained for each day between August 9 and August 23.

CHEMICAL ANALYSIS

Nitrogen Content

Nitrogen content of American basswood leaf tissue was determined by the Kjeldahl method (Pepkowitz 1942).

Other Chemical Components

Leaf manganese, iron, potassium, magnesium, calcium, zinc and copper contents were determined by atomic absorption spectrophotometry.

ROOT EXCAVATION METHODS

Two replicates of black pine, Norway spruce and honey locust saplings and two replicates of hybrid poplar and green ash saplings and seedlings were selected for study at the end of the 1979 growing season from both the landfill and control screening areas for a total of 28 trees. At the end of the 1977 growing season, two American basswood (Tilia americana) trees were selected for study from each of three gas-barrier trenches on the experimental landfill plot, one gas-barrier system on the control plot and from the landfill and control unmodified areas totaling eight trees from the landfill plot and four from the control. The entire root system of each tree was completely excavated by means of a small hand trowel from the point of emergence at the main stump to the root tips. Each root greater than 1 mm in diameter was followed to its end except in cases where it lay beneath an adjacent tree or had been broken.

After the individual roots had been exposed, the distance from the soil surface to the center of each root was measured at 30 cm (12 in.) intervals from the stump to and including the root tip.

STATISTICAL ANALYSIS

Analysis of variance, analysis of covariance, Student's "t" test, multiple regression, factor analysis, Chi-square analysis and correlation were used to analyze the data in this report (Zar 1974; Draper and Smith 1967; Harman 1977).

SECTION 6

RESULTS

SPECIES SCREENING EXPERIMENT

Relative Viability of Plants

Twenty-three plants on the landfill plot and 19 on the control plot died between the winter of 1977-1978 and the end of summer 1979 (Table 3). Most of these deaths were attributed to dry soil conditions. In addition, the 10 weeping willows on the control plot were cut down in the spring of 1978 because all the willows on the landfill plot had died from lack of moisture by the end of the 1977 growing season. Ninety percent of the euonymus shrubs on both plots were destroyed by rabbits, therefore, the remaining shrubs were removed from both plots during the fall of 1978. All the rhododendron shrubs on the landfill plot had succumbed to exposure, winter injury or lack of moisture by the end of 1977. Enough replicates of sixteen of the original 19 species remained alive during 1978 and 1979 to statistically evaluate their ability to tolerate landfill soil conditions.

TABLE 3. NUMBER OF TREE DEATHS IN SCREENING EXPERIMENT BETWEEN NOVEMBER 1977 AND OCTOBER 1979

Species	Landfill plot	Control plot
Black gum	1	0
Bayberry	1	0
Pin Oak	1	0
Japanese yew	1	5
Sweet gum	5	3
Euonymus	3	9
Weeping willow	6	0
Japanese black pine	0	1
Hybrid poplar (saplings)	1	0
Ginkgo	3	0
Norway spruce	1	1
American basswood	0	0
Red maple	0	0
American sycamore	0	0
Hybrid poplar (rooted cuttings)	0	0
White pine	0	0

(continued)

TABLE 3. (continued)

Species	Landfill plot	Control plot
Honey locust	0	0
Green ash	0	0
Total	23	19

Relative Growth of Surviving Plants

During 1978, the majority of species grew better on the control plot than on the landfill plot (Tables 4 and 5) (Figures 1 and 2). Black pine was the only species which produced both greater shoot length and stem area on the landfill plot than on the control plot. Bayberry and ginkgo produced the same amount of shoot growth but greater stem area on the landfill plot than on the control plot. Norway spruce, white pine and black gum had better stem growth, but less shoot growth on the experimental landfill plot compared to the control. American basswood had slightly less stem growth and slightly greater shoot length on the landfill than the control. In hybrid poplar (rooted cuttings) stem growth was similar on the landfill and control plots, whereas, shoot length was greater on the control. Red maple had equal shoot growth on both plots but significantly poorer stem growth on the landfill compared to the control plot. In Japanese yew, American sycamore, pin oak, hybrid poplar, sweet gum, honey locust and green ash both shoot and stem growth were lower on the landfill than on the control plot.

TABLE 4. AVERAGE SHOOT LENGTH* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1978 GROWING SEASON

Species	Shoot length (cm) Landfill	Control	Landfill as % control	Landfill tolerance rank
Black pine	24.3	21.5	113.1	1
American basswood	9.1	8.4	108.8	2
Ginkgo	.8	.8	100.0	3
Bayberry	13.7	13.9	99.1	4
Red Maple	28.1	28.8	97.4	5
Japanese yew	13.2	14.5	90.9	6
American sycamore	25.4	30.6	83.0	7
Hybrid poplar (rooted cuttings)	95.7	121.0	79.1	8
Black gum	14.0	17.8	78.9	9
White pine	11.6	15.7	74.0	10
Pin oak	22.7	39.4	73.3	11
Norway spruce	14.9	22.7	65.3	12
Hybrid poplar (saplings)	41.2	103.5	39.8+	13

(continued)

TABLE 4. (continued)

Species	Shoot length (cm) Landfill	Control	Landfill as % control	Landfill tolerance rank
Sweet gum	13.1	40.4	32.5‡	14
Honey locust	17.6	61.1	28.8+	15
Green ash	10.4	40.6	25.7+	16

* Average from 1 to 10 replicates depending on species.

\+ Significant @ P <.01.

‡ Significant @ P <.05.

TABLE 5. AVERAGE PERCENT STEM AREA INCREASE* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1978 GROWING SEASON

Species	Stem area* (%) Landfill	Control	Landfill as % control	Landfill tolerance rank
Black pine	51.0	20.1	253.3+	1
Bayberry	18.8	8.1	232.5‡	2
Norway spruce	27.9	12.2	228.5‡	3
Ginkgo	14.8	8.4	175.0	4
White pine	23.9	20.1	118.9	5
Black gum	40.1	37.0	108.2	6
American basswood	26.4	27.2	97.0	7
Hybrid poplar (rooted cuttings)	188.7	198.7	95.0	8
Red maple	50.7	79.5	62.8‡	9
Hybrid poplar (saplings)	133.2	216.7	61.4	10
Sweet gum	26.6	44.1	60.3	11
American sycamore	21.7	39.7	54.6	12
Green ash	37.9	73.6	51.6+	13
Pin oak	42.8	93.6	45.2+	14
Japanese yew	22.4	50.2	44.6+	15
Honey locust	29.2	86.5	32.8+	16

* Percent increase from March to October from 1 to 10 replicates depending on species.

\+ Significant @ P <.01.

‡ Significant @ P <.05.

Figure 1. Portion of the landfill screening area.

Figure 2. Portion of the control screening area.

During 1979, six of the 16 species produced more shoot growth on the landfill than on the control plot; however, one-half of the species (8) produced more stem area on the landfill plot than on the control (Tables 6 and 7). Honey locust, hybrid poplar rooted cuttings and white pine produced greater shoot length and stem area on the landfill plot than on the control plot. Black gum, black pine and American sycamore had better shoot growth but poorer stem growth on the experimental landfill plot compared to the control. Japanese yew, bayberry, American basswood, red maple and pin oak increased cross-sectional stem area more on the landfill than on the control plot but produced less shoot length. Norway spruce, sweet gum, ginkgo, green ash and hybrid poplar saplings produced smaller amounts of shoot and stem growth on the landfill compared to the control plot.

TABLE 6. AVERAGE SHOOT LENGTH* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1979 GROWING SEASON

Species	Shoot length (cm) Landfill	Control	Landfill as % control	Landfill tolerance rank
Honey locust	101.8	85.5	118.8	1
Black gum	30.9	26.5	116.6	2
Hybrid poplar (rooted cuttings)	107.8	98.2	109.8	3
Black pine	27.6	25.5	109.4	4
White pine	20.1	19.1	105.6	5
American sycamore	51.7	49.3	104.8	6
Japanese yew	24.9	26.0	95.5	7
Norway spruce	24.9	26.6	93.6	8
Bayberry	12.0	13.8	86.9	9
American basswood	18.7	23.7	79.2	10
Red maple	48.6	61.6	78.8‡	11
Sweet gum	35.7	48.9	73.1	12
Ginkgo	0.5	0.8	70.0	13
Pin oak	29.3	43.1	67.8	14
Green ash	34.1	59.5	57.4+	15
Hybrid poplar (saplings)	42.1	107.2	39.3+	16

* Average from 1 to 10 replicates depending on species.

\+ Significant @ P <.01.

‡ Significant @ P <.05.

TABLE 7. AVERAGE PERCENT STEM AREA INCREASE* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1979 GROWING SEASON

Species	Stem area (%*) Landfill	Control	Landfill as % control	Landfill tolerance rank
Japanese yew	62.4	38.5	161.9+	1
White pine	52.0	33.0	157.8+	2
Red maple	121.8	85.9	141.8+	3
Bayberry	31.3	23.1	135.6	4
Honey locust	142.8	105.3	135.6	5
Hybrid poplar (rooted cuttings)	130.3	104.4	124.8	6
American basswood	78.9	64.5	122.3	7
Pin oak	73.3	68.8	106.5	8
Norway spruce	39.5	41.5	95.1	9
Black pine	53.3	57.5	92.7	10
Ginkgo	13.2	16.7	79.2	11
American sycamore	48.1	62.4	77.2‡	12
Sweet gum	62.0	85.2	72.7+	13
Green ash	43.7	61.3	71.3+	14
Black gum	41.2	70.0	58.9+	15
Hybrid poplar (saplings)	55.0	127.0	43.3+	16

* Percent increase from March to October from 1 to 10 replicates depending on the species.

\+ Significant @ $P < .01$.

‡ Significant @ $P < .05$.

Assessing the ability of each species to tolerate or adapt to the landfill environment by compiling growth data from the first four years of experimentation can be approached in several ways.

First, total shoot growth for each species on both plots was calculated by totaling shoot length measurements for each replicate for the years 1976, 1977, 1978 and 1979. Average values for all replicates are presented in Table 8. Each species was ranked in order of relative tolerance to landfill conditions on the basis of the ratio of values for landfill growth to those of control. The highest values for total shoot growth on the landfill as percent of control were obtained for ginkgo (127.5%) and black gum (117.3%) whereas, the lowest tallies corresponded to sweet gum and hybrid poplar saplings.

TABLE 8. AVERAGE SHOOT LENGTH* FOR 16 SPECIES ON THE LANDFILL AND CONTROL PLOTS FROM 1976 THROUGH 1979 GROWING SEASON

Species	Landfill (cm)	Control (cm)	Landfill as % of control	Landfill tolerance rank+
Ginkgo	25.5	20.0	127.5	1
Black gum	92.9	79.2	117.3	2
Japanese yew	69.8	70.1	99.6	3
American sycamore	133.6	135.7	98.4	4
Japanese black pine	83.8	90.7	92.5	5
Hybrid poplar (rooted cuttings)	320.6	354.1	90.5	6
Bayberry	49.8	57.4	86.7	7
White pine	53.8	65.0	82.7	8
Norway spruce	56.6	69.8	81.1	9
American basswood	52.0	67.6	76.9	10
Red maple	111.0	150.4	73.8	11
Pin oak	77.2	115.8	66.7	12
Honey locust	135.6	217.7	62.3	13
Green ash	81.5	144.4	56.4	14
Sweet gum	65.8	128.3	51.3	15
Hybrid poplar (saplings)	76.0	331.5	22.9	16

* Each number is the sum of shoot length measurements from each living replicate from the years 1976, 1977, 1978 and 1979 from 1 to 10 replicates per species.

\+ The lower the number, the more tolerant the species is to landfill conditions.

Secondly, average stem area increase from March 1977 to the end of 1979 was computed for each species on both plots (Table 9). Each species was ranked in order of relative tolerance to the landfill environment with the highest rank given to that species which grew best on the landfill compared to the control and the lowest rank corresponding to that species which grew poorest on the landfill compared to the control plot. The highest values for stem increase on the landfill as percent on control were obtained for Japanese yew (176.2%) and white pine (133.0%) whereas, the lowest tallies corresponded to hybrid poplar saplings (39.5%) and green ash (37.7%).

TABLE 9. PERCENT STEM CROSS-SECTION AREA INCREASE* FOR 16 SPECIES FROM MARCH 1977 THROUGH OCTOBER 1979 ON THE LANDFILL AND CONTROL PLOTS

Species	Landfill (%)	Control (%)	Landfill as % of control	Landfill tolerance rank+
Japanese yew	188.4	106.9	176.2	1
White pine	174.0	130.8	133.0	2
Norway spruce	164.9	127.5	129.3	3
Black gum	641.7	539.5	118.9	4
Japanese black pine	275.3	233.8	117.8	5
American basswood	165.5	153.4	107.6	6
Ginkgo	25.8	29.9	86.3	7
Red maple	393.7	463.4	84.0	8
Bayberry	96.3	119.0	80.9	9
American sycamore	171.7	255.3	67.2	10
Pin oak	361.9	650.0	55.7	11
Honey locust	291.4	620.9	46.9	12
Sweet gum	307.7	731.6	42.0	13
Hybrid poplar (rooted cuttings)	9,534.5	23,993.4	39.7	14
Hybrid poplar (saplings)	295.0	1,165.8	39.5	15
Green ash	130.2	345.6	37.7	16

* Stem measurements from 1 to 10 replicates, depending on the species.

\+ The lower the number, the more tolerant the species is to landfill conditions.

Thirdly, rank values for shoot growth during 1976, shoot and stem growth in 1977 (both given in a previous report[1]), shoot and stem growth during 1978 (Tables 4 and 5) and shoot and stem growth during 1979 (Tables 6 and 7) were totaled for each species (Table 10). The values were aligned from lowest to highest with the most tolerant species (Japanese yew) represented by the lowest sum of tolerance ranks value and the species most sensitive to the landfill environment (hybrid poplar saplings) at the bottom of the table with the highest value.

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[1]EPA Publication 600/2-79-128. Adapting Woody Species and Planting Techniques to Landfill Conditions.

TABLE 10. SUM OF LANDFILL TOLERANCE RANKS* FOR SHOOT AND STEM MEASUREMENTS FROM 1976 THROUGH 1979

Species	Sum of tolerance rank values+	Landfill tolerance rank
Japanese yew	37	1
Japanese black pine	42	2
Black gum	45	3
Bayberry	45	3
Ginkgo	46	5
White pine	49	6
Norway spruce	50	7
Hybrid poplar (rooted cuttings)	50	7
American basswood	54	9
American sycamore	60	10
Red maple	60	10
Honey locust	72	12
Pin oak	77	13
Sweet gum	83	14
Green ash	87	15
Hybrid poplar (saplings)	102	16

* Each number is the sum of that species' rank in 7 rank lists relative to the other species. The 7 rank lists are the following: stem area increase measurements from 1977, 1978 and 1979, and shoot length measurements from 1976, 1977, 1978 and 1979.

\+ The lower the number, the more tolerant the species is to landfill conditions.

Finally, the Principal Axis Factor Method (Harmen 1967) was used to calculate average factor scores for each species on both plots (Table 11). The nature of this statistical procedure dictates that the final factor scores must add up to zero, thus, the presence of negative numbers in the table. The difference between the control and landfill plots was computed for each species. The species with the largest negative difference were ranked as the most tolerant to the landfill environment because a negative value indicated that growth was better on the landfill than on the control plot. The species with the largest positive difference (Hybrid poplar rooted cuttings) was rated as least tolerant of the landfill soil environment because growth on the landfill plot compared to the control was poorer than any other species.

The grand total of the landfill tolerance ranks for each species computed by summing the rank values from each of the above four methods of analyzing the compiled growth data is presented in Table 12. This composite ranking order identified black gum as the most landfill tolerant woody species of those tested.

TABLE 11. AVERAGE FACTOR SCORES* FOR 16 SPECIES FROM DATA FROM 1976 THROUGH 1979 ON THE LANDFILL AND CONTROL PLOTS

Species	Landfill	Control	Difference (control-landfill)	Landfill tolerance rank+
Black gum	-0.02	-0.14	-0.12	1
Japanese black pine	-0.23	-0.28	-0.05	2
Bayberry	-0.65	-0.69	-0.04	3
Ginkgo	-1.08	-1.11	-0.03	4
White pine	-0.61	-0.63	-0.02	5
American basswood	-0.57	-0.54	-0.03	6
Norway spruce	-0.57	-0.50	-0.07	7
Japanese yew	-0.43	-0.36	-0.07	8
Sweet gum	0.18	0.31	0.13	9
American sycamore	0.02	0.17	0.15	10
Red maple	0.15	0.53	0.38	11
Pin oak	-0.22	0.36	0.58‡	12
Hybrid poplar (saplings)	0.12	0.71	0.59‡	13
Green ash	-0.57	0.30	0.87‡	14
Honey locust	0.31	1.33	1.02‡	15
Hybrid poplar (rooted cuttings)	2.96	4.04	2.96‡	16

* Principal Axis Factor Method was used to calculate factor patterns and factor scores for shoot and stem data from 1976 through 1979.

\+ The lower the number, the more tolerant the species is to landfill conditions.

‡ Significant @ $P < 0.05$.

TABLE 12. RELATIVE TOLERANCE OF 16 SPECIES TO LANDFILL CONDITIONS*

Species	Sum of landfill tolerance rank values
Black gum (4, 8)+ -R$^{\Delta}$	10
Japanese yew (9, 4) -	13
Japanese black pine (10, 9) -	14
Ginkgo (7, 9) -S	17
White pine (10, 10) -S	21
Bayberry (9, 9) -	23
Norway spruce (8, 8) -S	26
American basswood (9, 10) -S	31
American sycamore (10, 10) -R	34
Red maple (9, 10) -I	41
Hybrid poplar (rooted cuttings) (10, 5) -R	44

(continued)

TABLE 12. (continued)

Species	Sum of landfill tolerance rank values
Pin oak (9, 10) -R	48
Sweet gum (1, 6) -R	51
Honey locust (10, 10) -R	52
Green ash (10, 10) -R	59
Hybrid poplar (saplings) (2, 7) -R	60

* Tolerance was established by totaling the landfill tolerance rank values for each species from Tables 8, 9, 10 and 11.

\+ Number of replicates living on the landfill and control plots respectively at the end of 1979.

Δ R=rapid growth rate, I=intermediate growth rate, S=slow growth rate, N=data not available - from Fowells (1965).

The variation between trees in total shoot growth and percent stem growth is represented for each species on both plots by the coefficient of variation (Tables 13 and 14). This statistic expresses sample variability relative to the mean of that sample by dividing the standard deviation by the mean value. There was less variability in both shoot and stem growth among landfill tolerant species on the landfill than on the control. However, the variability among replicates of those species relatively sensitive to the landfill soil conditions, i.e., those towards the bottom of Tables 13 and 14, was generally greater on the landfill than on the control plot.

Total shoot growth and stem diameter increase are presented in Table 15 in descending order from the highest growth on to the least amount of growth on the landfill. According to this list, hybrid poplar (from rooted cuttings) was the best total growth species, and ginkgo the least total growth species for planting on completed landfill sites.

TABLE 13. COEFFICIENTS OF VARIATION* FOR TOTAL SHOOT LENGTH FROM 1976 THROUGH 1979 OF 16 SPECIES+ ON LANDFILL AND CONTROL PLOTS

Species	Landfill	Control
Black gum	28.0	35.0
Japanese yew	24.0	33.6
Japanese black pine	23.6	30.7
Ginkgo	0.0‡	4.4
White pine	34.5	38.5
Bayberry	43.7	35.7
Norway spruce	31.7	39.3

(continued)

TABLE 13. (continued)

Species	Landfill	Control
American basswood	37.7	51.0
American sycamore	26.0	23.7
Red maple	33.1	32.8
Hybrid poplar (rooted cuttings)	22.8	17.8
Pin oak	29.4	17.9
Sweet gum	0.0Δ	9.0
Honey locust	25.0	20.9
Green ash	39.0	18.0
Hybrid poplar (saplings)	31.2	19.1

* Coefficient of Variation = $\frac{\text{standard deviation}}{\text{mean}}$ X 100.

\+ Species are listed from most tolerant to least landfill tolerant as given in Table 12.

‡ There was no variation in the data points.

Δ Only one tree living so standard deviation = 0.

TABLE 14. COEFFICIENTS OF VARIATION* FOR PERCENT STEM INCREASE FROM 1977 THROUGH 1979 FOR 16 SPECIES+ ON LANDFILL AND CONTROL PLOTS

Species	Landfill	Control
Black gum	41.3	46.8
Japanese yew	38.8	56.0
Japanese black pine	45.1	55.1
Ginkgo	50.2	102.6
White pine	45.4	63.8
Bayberry	31.1	51.1
Norway spruce	52.4	46.2
American basswood	29.6	57.8
American sycamore	230.9	41.9
Red maple	74.8	28.2
Hybrid poplar (rooted cuttings)	62.6	39.0
Pin oak	33.9	38.6
Sweet gum	0.0#	42.0
Honey locust	38.8	56.4
Green ash	41.5	37.4
Hybrid poplar (saplings)	39.1	32.7

* Coefficient of Variation = $\frac{\text{Standard deviation}}{\text{mean}}$ X 100.

\+ Species are listed from most tolerant to least landfill tolerant.

\# Only one tree living so standard deviation = 0.

TABLE 15. TOTAL SHOOT LENGTH* AND PERCENT STEM INCREASE+ FOR 16 SPECIES ARRANGED IN DESCENDING ORDER OF VALUES FROM 1976-1979 ON THE LANDFILL

Species	Shoot length (cm)	Species	Stem increase (%)
Hybrid poplar (rooted cuttings)	320.6	Hybrid poplar (rooted cuttings)	9534.5
Honey locust	135.6	Black gum	641.7
American sycamore	133.6	Red maple	393.7
Red maple	111.0	Pin oak	361.9
Black gum	92.9	Sweet gum	307.7
Japanese black pine	83.8	Hybrid poplar (saplings)	295.0
Green ash	81.5	Honey locust	291.4
Pin oak	77.2	Japanese black pine	275.3
Hybrid poplar (saplings)	76.0	Japanese yew	183.4
Japanese yew	69.8	White pine	174.0
Sweet gum	65.8	American sycamore	171.7
Norway spruce	56.6	American basswood	155.5
White pine	53.8	Norway spruce	164.9
American basswood	52.0	Green ash	130.2
Bayberry	49.8	Bayberry	96.3
Ginkgo	25.5	Ginkgo	25.8

* Each number is the sum of the average shoot length measurements from each living replicate for the years 1976 through 1979.

\+ Percent increase from March 1977 through 1979.

Soil Measurements

Measurements of numerous soil variables throughout the study were made in order to characterize the nature of the stress to which the plants were subjected on the landfill plot and to compare the values for these variables with those in the control plot (Table 16). Mean CO_2 and CH_4 content and temperature were significantly greater ($P<.01$) and O_2 and moisture content significantly lower on the landfill plot than on the control plot. Concentrations of CO_2 and CH_4 on the landfill plot were significantly higher at the deeper soil depths, (i.e. 90 cm) than in surface layers and O_2 readings were significantly lower at the 90 cm depth than at more shallow depths (Table 17). The levels of all soil nutrients except zinc and manganese were lower on the landfill plot than on the control plot, but not significantly so.

Carbon dioxide, O_2 and CH_4 concentrations at the 20 cm depth were all highly correlated with each other during the period 1977 through 1979 (Table 18). Levels of each of the soil gases were also significantly correlated with temperatures recorded at the 20 cm depth in the soil.

TABLE 16. MEAN VALUES* FOR SOIL VARIABLES ON LANDFILL AND CONTROL PLOTS IN 1978 AND 1979

Soil Variable	Landfill plot 1978	Landfill plot 1979	Control plot 1978	Control plot 1979
Temperature °C	19.0b+	18.3b	17.7a	17.3a
% Moisture content	8.0a+	10.1b	10.8bc	12.2c
Conductivity (1-2)	0.1	0.1	0.1	0.1
Organic matter %	1.8	1.8	2.3	2.1
% Sand	82.8	83.1	79.0	75.1
pH	4.5	6.1	4.5	5.9
lbs/A				
Mg	37	62.3	114	124.1
P	79	147.7	60	141.1
K	123	105.7	241	135.0
Ca	178	1591	567	2036
NO_3	29.7	16.7	80	36.0
NH_4	10	9.7	22	14.0
ppm				
Fe	79	65.5	153	75.5
Cu	4.1	2.9	4.7	3.9
Zn	7.5	5.4	4.3	7.7
Mn	19	14.2	17	31.5
B	0.30	0.24	0.25	0.29

* Samples collected at the 20 cm depth. Each gas concentration value is the mean of 320 readings.

\+ Row means followed by different letters are significantly different at P<.01.

TABLE 17. SOIL GAS CONCENTRATIONS DURING 1978 AND 1979 AT THE 20 cm*, 60 cm+ AND 90 cm+ DEPTHS ON THE LANDFILL AND CONTROL PLOTS.

Soil Depth (cm)	Year	Landfill			Control		
		$\%O_2$	$\%CO_2$	$\%CH_4$	$\%O_2$	$\%CO_2$	$\%CH_4$
20	1978	18.1b#	3.8a	0.4a	20.0b	1.2b	0.0a
	1979	17.2b	4.1a	0.4a	19.8b	0.9a	0.0a
60	1978	18.1b	6.7b	1.8b	18.2a	1.2b	0.0a
	1979	18.3b	8.7b	1.7b	18.8a	1.2b	0.0a
90	1978	12.7a	24.9d	16.9d	18.3a	1.3b	0.0a
	1979	13.7a	22.1c	14.2c	18.9a	1.2b	0.0a

* Values represent mean from 640 readings on the landfill plot and 80 readings on the control plot during 1978 and 1979.

\+ Values represent mean from 120 readings on the landfill plot and 40 readings on the control plot during 1978 and 1979.

\# Column means followed by different letters are significantly different from each other @ P<.01.

TABLE 18. CORRELATION* AMONG SOIL GASES+ AND SOIL TEMPERATURES ON THE LANDFILLL PLOT

Gas	Carbon dioxide	Methane	Temperature
Oxygen	-0.98#	-0.95#	-0.72#
Carbon dioxide	--	+0.94#	+0.72#
Methane	--	--	+0.71#

* Each number represents the correlation coefficient (r) between the two indicated soil parameters for data collected during 1977, 1978 and 1979.

\# Significant at P<0.01.

\+ Samples collected at the 20 cm depth. Each value was computed on 960 readings.

Variability around the mean CO_2, O_2 and CH_4 concentrations was greater in the landfill soil than in the control soil demonstrating that high levels were occasionally recorded in the landfill soil (Figures 3, 4 and 5).

Soil pH values in the landfill soil differed very little from levels in the control soil (Figure 6). The pH dropped from approximately 5.0 in 1977 to 4.5 in 1978 on both plots only to rise to 6.2 and 6.3 (control and landfill respectively) when the soil was amended with proper amounts of limestone.

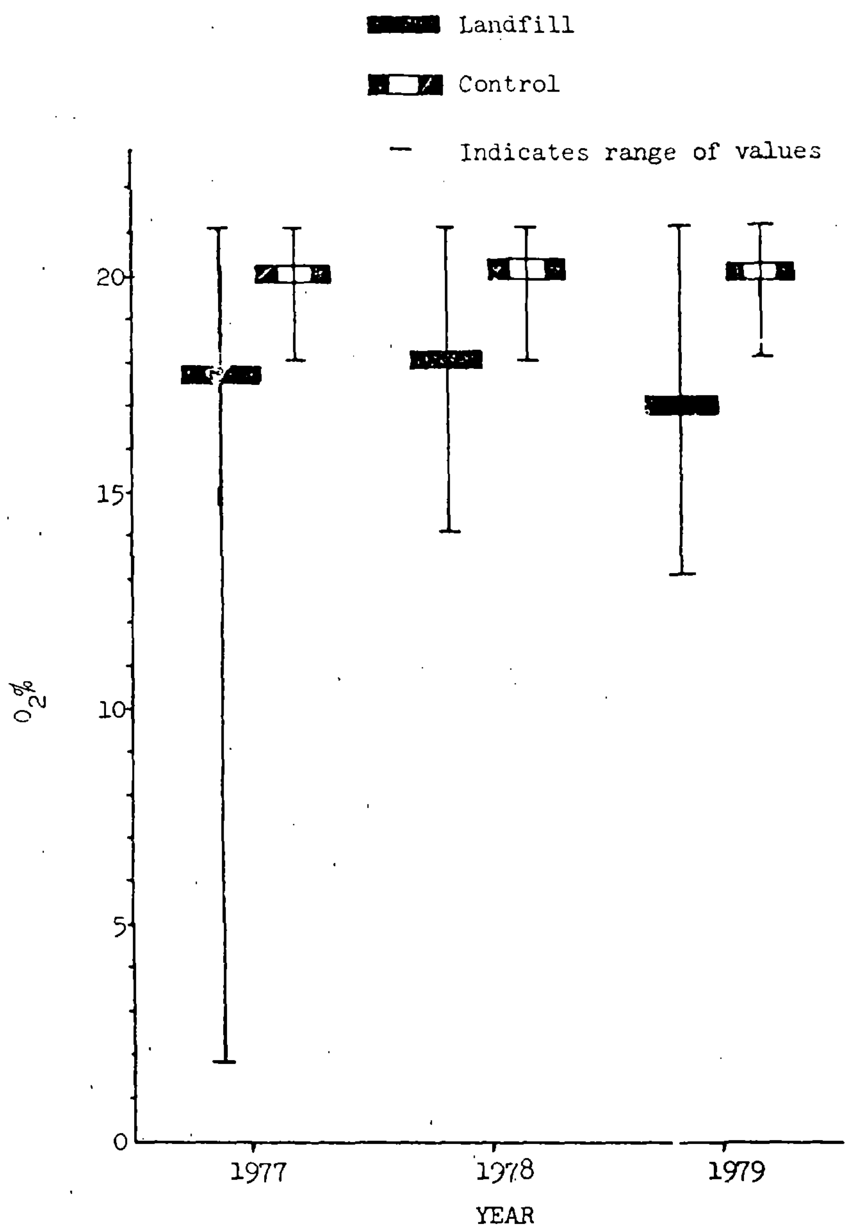

Figure 3. Mean soil oxygen concentrations (% volume) at the 20-cm depth in the landfill and control soil during 1977, 1978 and 1979.

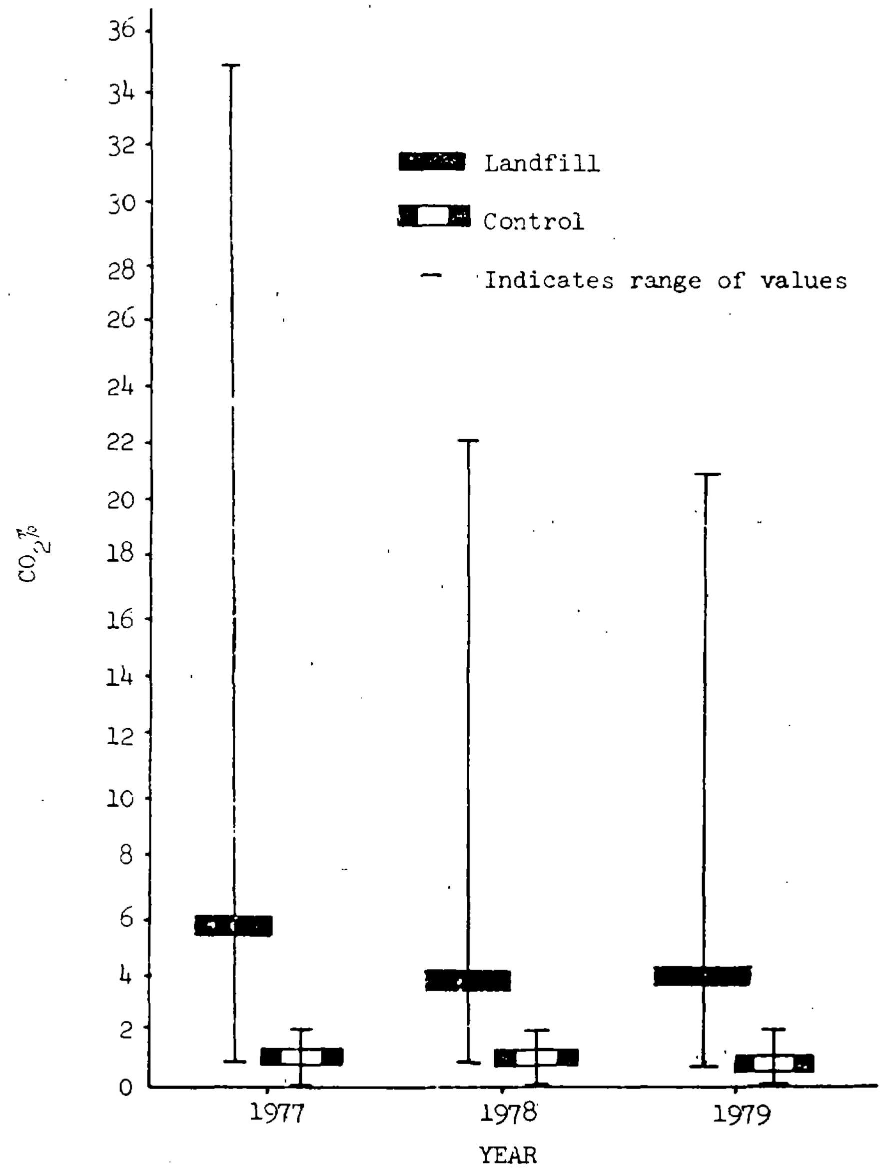

Figure 4. Mean soil carbon dioxide concentrations (% volume) at the 20-cm depth in the landfill and control soil during 1977, 1978 and 1979.

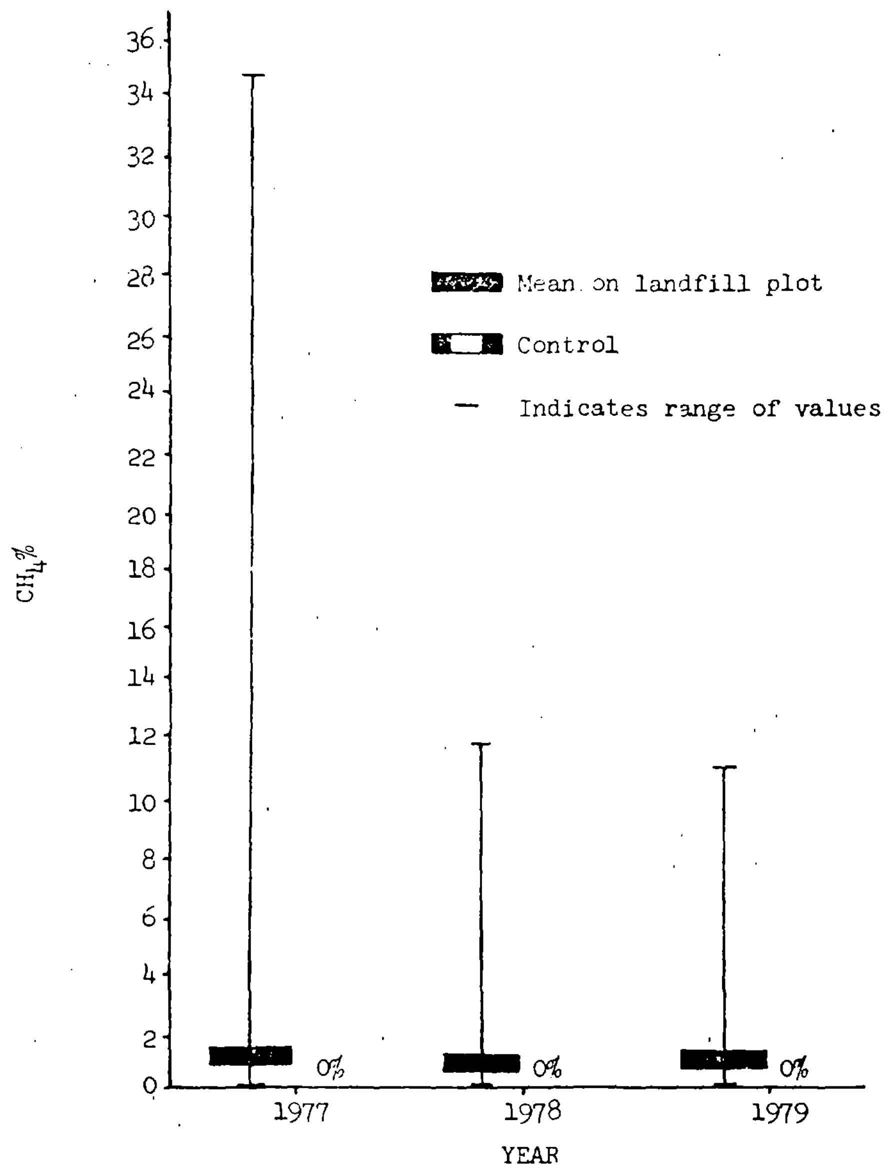

Figure 5. Mean soil methane concentrations (%volume) at the 20-cm depth in the landfill and control soil during 1977, 1978 and 1979.

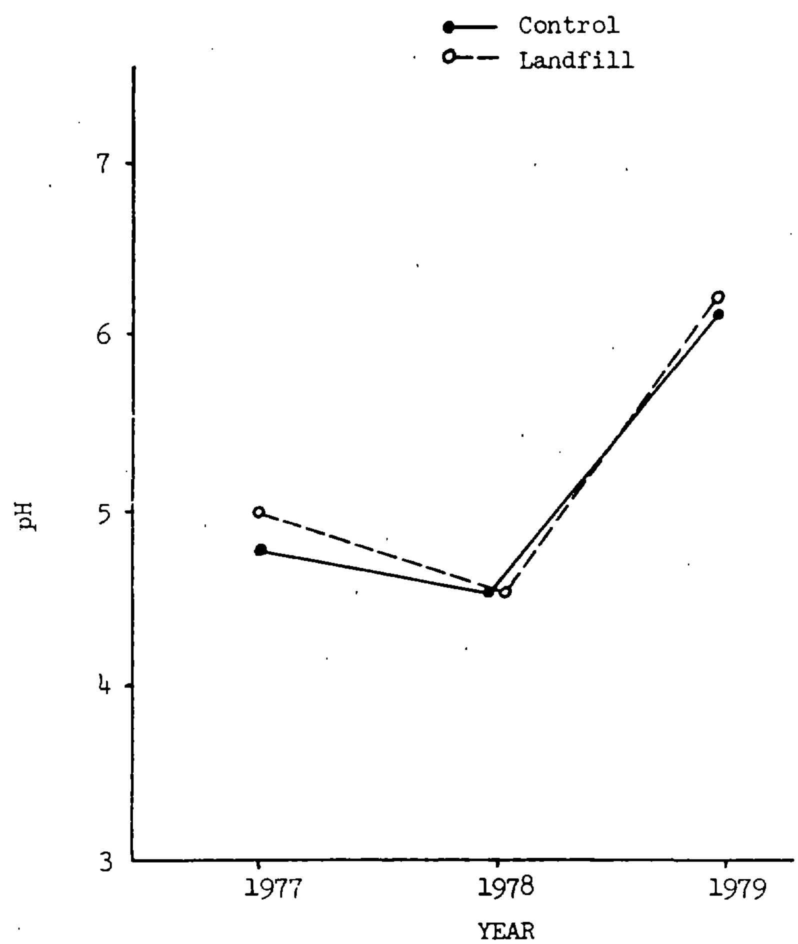

Figure 6. Soil pH levels during 1977, 1978 and 1979.

TABLE 19. SOIL VARIABLES WHICH CORRELATE WITH SHOOT AND STEM GROWTH OF SPECIES IN THE LANDFILL SPECIES SCREENING EXPERIMENT*

Species	Soil Variables
Shoot Growth	
Black pine	None
American basswood	M.C.+, B.D., O_2*M.C., O_2*B.D.
Ginkgo	None
Bayberry	None
Red maple	None
Japanese yew	None
American sycamore	M.C., B.D., O_2*M.C., O_2*B.D.
Hybrid poplar (rooted cuttings)	None
Black gum	O_2, B.D., O_2*M.C.
White pine	None
Pin oak	None
Norway spruce	O_2
Hybrid poplar (saplings)	None
Sweet gum	O_2, M.C., B.D., O_2*M.C., O_2*B.D.
Honey locust	O_2, M.C., B.D., O_2*M.C., O_2*B.D.
Green ash	None
Stem Growth	
Black pine	None
Bayberry	None
Norway spruce	None
Ginkgo	None
White pine	None
Black gum	O_2, M.C.
American basswood	None
Hybrid poplar (rooted cuttings)	None
Red maple	None
Hybrid poplar (saplings)	None
Sweet gum	None
Sycamore	None
Green ash	O_2, O_2*B.D.
Pin oak	O_2*B.D.
Japanese yew	O_2, M.C., O_2*B.D.
Honey locust	None

* Species are arranged in descending order from most tolerant of landfill conditions to least tolerant.

\+ M.C.=moisture content, B.D.=bulk density, O_2=oxygen, O_2* B.D. = product of O_2 level and B.D. level, O_2 *M.C. =product of O_2 level and M.C. level.

Mean soil moisture content on the landfill and control plots from 1977 through 1979 is represented in Figure 7. Moisture content was consistently lower in the landfill plot than in the control. Soil moisture was maintained at adequate levels throughout 1979 by natural rainfall. Both plots were frequently irrigated during 1977 and 1978 in order to maintain moisture at levels high enough to prevent plant drought injury.

In order to investigate the effects of soil environment on tree growth a regression analysis was performed for shoot and stem growth for each of the 16 surviving species using soil O_2, moisture content (M.C.), bulk density (B.D.) and the interactions of O_2 with M.C. and O_2 with B.D. as independent variables (Table 19). The results of these analyses showed that soil parameters were more highly correlated with the intolerant species (those at the bottom of Table 19) than with the more tolerant species (those at the top of Table 19).

GAS-BARRIER EXPERIMENT

The following section reports on data collected from American basswood trees planted in the gas-barriers in 1976. Basswoods in the trench barrier areas were harvested in the spring of 1978 and replaced with seedlings of black gum, honey locust and pin oak.

Relative Viability of Plants

Six black gum, 5 pin oak and 3 honey locust trees died in the barrier trenches and on landfill and non-landfill unmodified areas during 1978 and 1979 (Table 20).

TABLE 20. NUMBER OF DEAD TREES IN LANDFILL AND CONTROL GAS-BARRIER TRENCHES AND IN UNMODIFIED LANDFILL AND CONTROL AREAS*

	Species			
Area	Black gum	Pin oak	Honey locust	Total
Control trench	1	1	1	3
Gravel/plastic/vents trench	1	1	0	2
Clay/vents trench	1	2	0	3
Clay trench	1	1	0	2
Unmodified landfill area	1	0	1	2
Unmodified control area	1	0	1	2
Total	6	5	3	14

* Six replicates of each species were originally planted in each area in Spring, 1978.

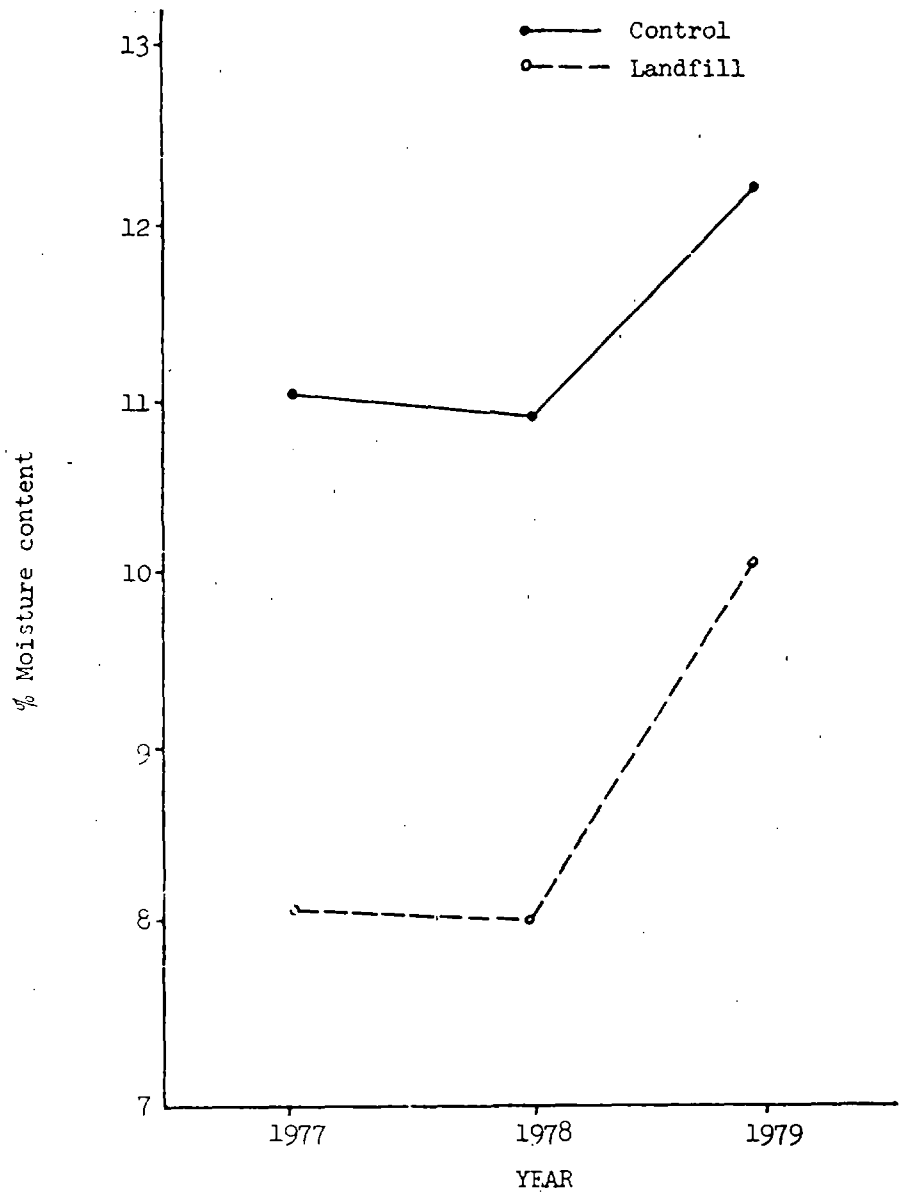

Figure 7. Soil moisture content (% dry weight) in the top 20-cm of landfill and control soil during 1977, 1978 and 1979.

Relative Growth of Surviving Plants

In the surviving trees, black gum shoot growth was statistically similar in all six experimental areas during 1978; however, in 1979, shoot growth in the gravel/plastic/vents trench was significantly greater than in any other area (Table 21). Pin oak shoot growth was similar for all areas on the landfill plot. The differences between the control trench and unmodified control area and between clay trench and unmodified control area were significant at $P<.01$ during 1978. No significant differences were identified for pin oak shoot growth in 1979. Honey locust shoot growth during 1978 and 1979 was significantly greater ($P<.01$) in the gravel/plastic/vents trench than in all other areas.

Shoot and stem measurements were collected from American basswood and Japanese yew on the two landfill mounds, the control mound and on the unmodified landfill and control areas to determine if the growth of woody plants in mounded soil areas would be better than in unmounded areas (Table 22). American basswood growth was significantly improved in the landfill mound lined with a 30 cm (12 in) clay barrier over that in the unmodified landfill area during the first three years of the study period (1976-1978). During 1978, shoot and stem growth of yew in the clay-lined mound and stem growth in the unlined mound was significantly greater than in the unmodified landfill area but not in 1979.

Soil Variables

Soil CO_2 and CH_4 concentrations in the clay/vents trench were significantly higher and O_2 significantly lower than in the control trench (Table 23). Soil moisture in the three landfill trenches was significantly lower than in the control trench (Table 23).

The most striking nutrient difference among areas was the low available phosphorus, high NH_4 and high Fe in the clay/vents compared to the other three areas. Cu, Zn and Mn content were also highest in the clay/vents trench.

Basswood Growth Parameters

Measurements of four growth parameters for the nine gas-barrier areas during 1977 are shown in Table 24. Basswood root biomass, basal stem area increase and shoot length in the unmodified landfill area were significantly reduced compared to the unmodified control; however, there was no significant difference among areas for leaf weight. Basswood growth was also significantly reduced ($P<.01$) on the landfill mound and landfill clay mound compared to control mound for each of the four growth parameters. Root biomass in the three landfill trenches was not significantly reduced ($P<.01$) below that in the control trench; however, for the other three parameters, growth was less in the clay/vents trench, unchanged in the clay trench and significantly higher ($P<.01$) in the gravel/plastic/vents trench compared to the control trench.

Growth on the landfill mounds and trenches was also compared with that

TABLE 21. MEAN SHOOT LENGTH (cm) FOR TREES IN EACH GAS-BARRIER TRENCH AND UNMODIFIED AREA FOR 1978 AND 1979

Area	Black gum		Pin oak		Honey locust	
	1978	1979	1978	1979	1978	1979
Control trench	12.0a*	25.1a	9.8a	18.2a	30.9a	70.1a
Gravel/plastic/vents trench	9.2a	52.1b	13.6ab	20.8a	91.9b	135.9c
Clay/vents trench	10.3a	26.2a	13.3ab	24.3a	36.5a	73.1a
Clay trench	10.5a	28.9a	11.5a	19.0a	25.2a	83.6a
Unmodified control area	11.2a	22.3a	18.1b	25.6a	38.6a	118.4b
Unmodified landfill area	13.0a	23.5a	15.5ab	17.8a	----+	70.6a

Species: Black gum, Pin oak, Honey locust.

* Column means followed by different letters are significantly different from each other @ $P<.01$.

\+ All shoots were destroyed by rabbits.

TABLE 22. SHOOT LENGTH AND PERCENT STEM AREA INCREASE* FOR AMERICAN BASSWOOD AND JAPANESE YEW ON LANDFILL AND CONTROL MOUNDS AND UNMODIFIED AREAS DURING THE YEARS 1976 THROUGH 1979

Area	Species	1976 Shoot Length (cm)	1976 Stem Increase (%)	1977 Shoot Length (cm)	1977 Stem Increase (%)	1978 Shoot Length (cm)	1978 Stem Increase (%)	1979 Shoot Length (cm)	1979 Stem Increase (%)
Unmodified	Jap. Yew	11.9	-	20.0	24.0	14.5	50.2	26.0	38.5
Control	Basswood	19.3	-	17.2	50.0	8.4	27.2	23.7	64.5
Unmodified	Jap. Yew	12.7	-	5.5	45.0	13.2	22.4	24.9	52.4
Landfill	Basswood	18.9	-	9.7	26.8	9.1	26.4	18.7	78.9
Control	Jap. Yew	12.7	-	4.7	37.0	14.8	20.1	21.2	42.7
Mound	Basswood	19.0	-	17.0	30.0	26.1	32.1	29.9	41.2
Landfill	Jap. Yew	17.5	-	4.7	14.0	17.2	51.2+	18.7	61.1
Mound	Basswood	27.9*	-	16.9	31.3	29.1+	29.1	21.2	59.1
Landfill	Jap. Yew	18.0	-	7.0	26.2	24.1+	41.6+	27.7	49.8
Clay Mound	Basswood	30.9*	-	21.6+	60.0+	31.2+	32.8+	23.5	74.8

* Stem measurements were not collected during 1976.

\+ Significantly different from unmodified landfill area @ P<.01.

TABLE 23. MEAN SOIL VARIABLE VALUES* IN EACH GAS-BARRIER TRENCH DURING 1978 AND 1979

Soil variable	Control trench 1978	Control trench 1979	Gravel/plastic vents trench 1978	Gravel/plastic vents trench 1979	Clay/vents vents trench 1978	Clay/vents vents trench 1979	Clay trench 1978	Clay trench 1979
% O_2	20.1a+	20.0a	19.4b	19.2a	17.1b	17.1b	19.6a	18.21a
% CO_2	1.2	1.0b	1.4b	1.9b	6.8a	5.4a	2.1b	1.9b
% CH_4	0.0	0.0a	0.0a	0.0a	4.8c	2.4c	1.2b	0.8b
% Moisture content	10.1	12.1b	8.7a	9.2a	9.2a	10.1a	8.9a	10.0a
Conductivity	< 0.10	0.10	< 0.10	0.10	< 0.10	0.10	< 0.10	0.10
% Organic matter	3.2	3.1	2.5	2.9	3.1	3.0	2.7	3.1
pH	4.7	5.8	4.8	5.9	5.3	6.1	5.3	6.1
lbs/A								
Mg	51	6.2	50	49	59	60	97	98
P	121	141	115	118	15	75	223	191
K	122	121	155	124	83	98	110	121
Ca	205	891	134	610	223	841	178	716
NO_3	17	16	13	15	9	12	4	17
NH_4	19	19	8	12	48	50	12	21
ppm								
Fe	82	91	70	72	210	121	51	60
Cu	4.8	4.3	4.5	4.8	5.6	5.2	3.8	5.2
Zn	5.2	5.2	5.5	6.2	6.0	6.0	5.4	5.1
Mn	17.9	16.1	18.0	19.1	26.0	25.0	18.5	19.2
B	0.48	0.21	0.63	0.51	0.32	0.41	0.57	0.52

* Values are average of 20 readings collected at the 20 cm depth from late April thru mid-September.

\+ Row means followed by different letters are significantly different at $P<.01$.

TABLE 24. MEAN VALUES FOR AMERICAN BASSWOOD GROWTH PARAMETERS IN GAS-BARRIER AREAS DURING 1977

Area	Root biomass (mg)	Stem area (% increase*)	Leaf weight (g)	Shoot length (cm)
Unmodified control	1865ab+	50.0c	1.21b	18.6e
Unmodified landfill	572a	26.8b	1.01b	9.7b
Control mound	2838b	76.6d	6.7 e	34.5g
Landfill mound	622a	31.3b	1.9 c	16.9e
Landfill clay mound	930a	60.0c	3.4 d	21.6f
Control trench	1901ab	30.0b	2.0 c	13.3c
Landfill clay trench	1069a	23.9b	2.21c	14.2cd
Landfill clay/vents trench	153a‡	0.0a	0.02a	16.8a
Landfill gravel/plastic/ vents trench	800a	73.3d	4.0 d	22.8f

* % increase from March to September.

\+ Column means followed by different letters are significantly different @ P<.01.

‡ Only one of the original six trees was alive at the end of 1977.

on the unmodified landfill area, thus allowing for an assessment of the ability of each of these five areas to promote better growth than the unmodified landfill. None of the trees in the five gas-barrier areas produced significantly more root biomass than in the unmodified landfill area. On the other hand, both the clay mound and gravel/plastic/vents trench produced significantly more stem area, leaf weight and shoot length than did the unmodified area. The landfill mound and clay trench produced greater leaf weight and shoot length, but similar stem area increase compared with the unmodified landfill area. Basswood growing in the clay/vents trench produced significantly less stem increase leaf weight or shoot length than in any other area.

Foliar Nutrient Uptake By American Basswood

American basswood leaf mineral content in the gas-barrier areas is given in Table 25. Mineral content of the foliage of trees from the unmodified landfill area for seven of the eight elements (nitrogen, potassium, magnesium, calcium, manganese, zinc and copper) was similar to that in the unmodified control area. Iron alone was significantly higher ($P<.05$) in content on the control plot. Nitrogen, calcium, manganese, zinc and copper contents did not differ significantly ($P<.05$) among the two landfill mounds and the control mound. However, the potassium content for trees was lower in the landfill mound and the iron content on the landfill mound and landfill-clay mound, higher than for trees on the control mound.

The most striking feature of the mineral content data was that American basswood foliage in the clay/vents trench contained significantly ($P<.05$) more magnesium and iron and significantly less nitrogen, potassium and manganese than did any other area including the control trench. The zinc concentration in the clay/vents trench did not differ significantly however, from those in any other trench. The nitrogen and potassium contents in the clay and gravel/plastic/vents trenches were significantly higher than in the control trench; however, no differences were detected for zinc and copper. Magnesium and calcium contents were lower for the clay trench and similar for the gravel/plastic/vents trench when compared to the control trench.

The increased ability of American basswoods growing in the landfill mounds and trenches to accumulate nutrients compared to unmodified conditions, can be assessed by comparing tissue element content in the trenches and mounds with contents in the unmodified landfill area (Table 25). The differences between the two landfill mounds and unmodified landfill area for potassium, calcium, zinc and copper were insignificant ($P<.05$) but the nitrogen content in both mounds was significantly greater than in the unmodified area. Although tissue magnesium content in the two mounds differed very little from that in the unmodified area, the clay mound contained significantly more magnesium than did the landfill mound and the unmodified area. American basswood contained a higher iron content in the landfill mound than in the unmodified area, but trees from the clay mound did not. The iron, zinc and copper contents in the clay and gravel/vents trenches did not significantly ($P<.05$) differ from those in the unmodified landfill area; however, nitrogen and potassium contents were increased significantly over the unmodified area in both trenches. Although the difference was very small, the magnesium content of American basswoods in the gravel/plastic/vents trench

TABLE 25. MINERAL ELEMENT CONTENT* OF AMERICAN BASSWOOD LEAF TISSUES IN GAS-BARRIER AREAS

Area	N %	K (X5000 ppm)	Mg (X5000 ppm)	Ca (X5000 ppm)	Mn (X500 ppm)	Fe (X200 ppm)	Zn (X500 ppm)	Cu (X200 ppm)
Unmodified control	3.13b+	2.91c	0.91a	2.71c	5.91cd	6.46d	1.58a	0.71a
Unmodified landfill	3.17b	2.71bc	0.92a	2.79c	6.20cd	5.93bc	1.48a	0.77a
Control mound	3.61c	3.03cd	0.93a	2.95c	6.48d	4.63a	1.89a	0.76a
Landfill mound	3.51c	2.60b	0.95a	2.77c	6.55d	6.48d	1.84a	0.86ab
Landfill clay mound	3.98c	2.82bc	1.00b	2.85c	6.73d	5.93bc	1.65a	0.78a
Control trench	3.18b	[illegible]	1.02b	2.52bc	3.62b	5.70b	1.23a	0.81ab
Landfill clay trench	3.[illegible]c	3.22d	0.89a	2.08a	3.42b	5.88bc	1.58a	0.76a
Landfill clay/ vents trench	2.60a	2.13a	1.16c	1.77a	1.[illegible]5a	7.60c	1.58a	0.89b
Landfill gravel/plastic vents trench	3.53c	3.37d	1.00b	2.48bc	5.95cd	6.20cd	1.14a	0.79a

* Each number is the mean of six replicate trees.

+ Column means with different letters are significantly different @ P<.05.

was significantly greater than that of trees in the landfill unmodified area.

Total mineral element uptake per branch was calculated for each tree and averaged for each experimental area (Table 26). The unmodified control area did not differ from the unmodified landfill screening area for any of the eight elements. In the landfill mound and landfill clay mound, American basswood accumulated less of every element than did trees on the control mound. The relative nutrient accumulation by American basswood among the four trenches was identical for each nutrient, i.e. the trees in the clay/vents trench accumulated less, those in the clay trench accumulated approximately the same and those in the gravel/plastic/vents trench accumulated more of each element than the control trench (Table 26).

Total accumulation per branch for each landfill barrier area was compared with the unmodified landfill area. The landfill mound and clay trench mineral element values did not differ significantly from the unmodified landfill screening area for any element except copper, which was significantly greater ($P<.05$) in these two areas than in the unmodified area. Trees in the landfill clay mound and gravel/plastic/vents trench accumulated significantly more of every element than did those in the unmodified area. On the other hand, total element uptake per branch for trees in the clay/vents trench was significantly lower than for those in the unmodified landfill area, except for copper which did not differ significantly ($P<.05$) from the screening area.

Soil Gas, Temperature, Moisture Content and Bulk Density Analyses

The soil oxygen and moisture contents on the unmodified landfill plot during 1977 were significantly reduced ($P<.01$) when compared to the control plot (Table 27). On the other hand, carbon dioxide, methane and soil temperature were significantly increased in the unmodified landfill plot. There was little difference in bulk density of two soils. The two landfill mounds did not differ from the control mound in any of the soil parameters except for soil moisture, which was significantly reduced on both landfill mounds.

The O_2 content was significantly lower and the CO_2 and CH_4 contents significantly higher in the clay trench and clay/vents trench than in the control trench. Soil temperature in the clay/vents and gravel trenches was significantly higher than in the control trench; whereas, bulk density was lower in the clay/vents and gravel/plastic/vents trenches. Soil bulk density in the clay trench was not significantly lower in the clay trench and gravel/plastic/vents trench compared to the control, however, moisture content in clay/vents trench was not significantly different from the control trench.

Soil Nutrient Analyses

The average nitrate (NO_3^-), ammonium (NH_4^+) nitrogen, potassium and manganese content in each area are given in Table 28 for samples collected on two separate dates in 1977. The $NO_3^-:NH_4^+$ ratios in June were relatively similar for all areas; however, by October, the $NO_3^-:NH_4^+$ ratio in the clay/vents trench was about half that in any other area either on the landfill or

TABLE 26. TOTAL AMERICAN BASSWOOD UPTAKE OF MINERAL ELEMENTS PER BRANCH* IN NINE EXPERIMENTAL AREAS

Area	Mn (mg)	Fe (X400 ug)	K (X10 mg)	Mg (X10 mg)	Ca (X10 mg)	Zn (mg)	Cu (400 ug)	N (X100 mg)
Unmodified control	6.8b+	7.5b	3.4b	1.1b	3.1b	1.8bcd	0.8a	3.6bc
Unmodified landfill	6.2b	5.9b	2.7b	0.9b	2.9b	1.5bc	0.7a	3.2bc
Control mound	45.6d	32.6e	21.3e	6.5e	20.8d	13.3f	5.4e	25.4f
Landfill mound	12.6b	12.3bc	4.9bc	1.8bc	5.3bc	3.5cde	1.6bc	6.6bcd
Landfill clay mound	22.9c	20.2cd	9.6cd	3.4cd	9.7c	5.6e	2.6cd	11.8de
Control trench	6.7b	10.5bc	4.7bc	2.0bc	6.6bc	2.2bcd	1.5bc	5.9bcd
Landfill clay trench	7.6b	12.8bc	7.1bc	2.0bc	4.6b	3.5cde	1.9cd	7.5cd
Landfill clay/ vents trench	0.3a	1.6a	0.4a	0.2a	0.4a	0.3a	0.2a	0.7a
Landfill gravel/ plastic/vents trench	23.7c	24.6de	13.4de	3.9d	9.9c	4.5e	3.1d	14.0e

* Uptake per branch = Average weight of leaves per branch X mineral concentration (ppm).

\+ Column means with different letters are significantly different @ P<.05.

TABLE 27. LEVELS* OF SOIL GASES, TEMPERATURE, SOIL MOISTURE AND BULK DENSITY+ IN THE GAS-BARRIER AREAS DURING 1977

Area	O_2 (%)	CO_2 (%)	CH_4 (%)	Temperature (°F)	Soil moisture (% dry wt.)	Bulk density (g/cc)
Unmodified control	19.7d#	1.2a	0.0a	64.3a	11.0d	1.82b
Unmodified landfill	17.8c	5.5b	0.9b	66.3b	8.1b	1.85b
Control mound	19.4d	1.2a	0.0a	64.1a	10.7d	1.45a
Landfill mound	20.3d	0.8a	0.0a	64.3a	7.3a	1.33a
Landfill clay mound	20.3d	0.8a	0.0a	64.3a	7.5a	1.44a
Control trench	19.6d	1.2a	0.0a	63.2a	10.5d	1.72b
Landfill clay trench	16.3b	7.0b	0.7b	65.2ab	8.4b	1.67b
Landfill clay/vents trench	4.3a	22.8c	11.8c	70.7c	11.0d	1.41a
Landfill gravel/ plastic/vents trench	19.8d	1.3a	0.0a	70.1c	9.0c	1.29a

* Each value is the average of 30 individual measurements.

\+ Bulk density was measured once in mid-summer at the same points gas samples were collected.

\# Column means followed by different letters are significantly different @ $P < .01$.

TABLE 28. LEVELS OF SELECTED NUTRIENTS* IN EACH OF THE GAS-BARRIER AREAS (1977)

	NO_3 (ppm)		NH_4 (ppm)		$NO_3^-:NH_4^+$ Ratio		K (ppm)		Mn (ppm)	
	June	Oct.	June	Oct.	June	Oct.	June	Oct.	June	Oct.
Control	52	29	262	11	0.20	2.6	173	104	85	21
Landfill	33	14	185	5	0.18	2.8	178	69	41	6
Control mound	67	42	280	11	0.24	3.8	200+	102	77.5	14
Landfill mound	28	7	290	2	0.10	3.5	200+	92	50	8.5
Landfill clay mound	23	20	170	8	0.14	2.2	177	119	72.5	11
Control trench	31	15	180	3	0.17	5.0	192	95	44	12.5
Landfill clay trench	25	6	140	2	0.18	3.0	192	84	50	6
Landfill clay/ vents trench	30	6	198	6	0.15	1.0	168	62	55	45
Landfill gravel/ plastic/vents trench	60	10	310	4	0.19	2.5	200+	80	90	6.5

* Since each nutrient was measured once in each area on each date, statistical analysis was not possible.

control plot. There were no other discernable soil nutrient trends other than a small decrease from June to October in the manganese concentration of the clay/vents trench compared to a relatively large decrease in all other areas, resulting in a high manganese (45 ppm) concentration by October in the clay/vents trench (Table 28).

Soil bulk density and root biomass were both correlated with tree nutrient uptake in the nine barrier areas (Table 29). Since root biomass is apparently influenced by landfill soil conditions and root biomass is positively correlated with total nutrient uptake, then the efficiency with which the root system accumulates nutrients may be assessed by analyzing total nutrient uptake differences between areas after removing the linear effect of root biomass on nutrient uptake. If the effects of bulk density and root biomass on nutrient uptake are removed by analysis of covariance, the efficiency of nutrient accumulation can be evaluated since the linear relationship of root biomass and bulk density with nutrient accumulation/branch is removed. After adjusting the eight nutrient means in each area for these two effects (Table 30), nutrient accumulation in the gravel/plastic/vents trench and clay mound was no longer significantly greater than that in the experimental screening area as it was with the unadjusted means (Table 28). Therefore, basswoods in four of the five gas-barrier areas (both mounds, gravel trench, clay trench) have accumulated eight nutrient elements as efficiently as those in the unmodified landfill and unmodified control areas (Table 30). However, nutrient accumulation efficiency was severely reduced in the clay/vents trench where the landfill gas concentration was significantly greater than in any of the above areas (Table 30).

TABLE 29. CORRELATION COEFFICIENTS OF ROOT BIOMASS AND SOIL BULK DENSITY WITH TOTAL NUTRIENT UPTAKE FOR EIGHT NUTRIENTS IN AMERICAN BASSWOOD LEAF TISSUE

Tissue nutrient	Root biomass	Bulk density
Mn	0.64+	-0.46‡
Fe	0.59+	-0.44‡
K	0.66+	-0.46‡
Mg	0.70+	-0.44‡
Ca	0.72+	-0.47‡
Zn	0.75+	-0.51‡
Cu	0.69+	-0.49‡
N	0.69+	-0.44‡

+ Significant @ P<.01.

‡ Significant @ P<.05.

TABLE 30. AMERICAN BASSWOOD ELEMENT UPTAKE PER BRANCH* FOR EIGHT NUTRIENTS IN NINE EXPERIMENTAL AREAS ADJUSTED FOR BULK DENSITY AND ROOT BIOMASS

Area	Nutrient							
	Mn (mg)	Fe (X400 ug)	K (X10 mg)	Mg (X10 mg)	Ca (X10 mg)	Zn (mg)	Cu (X400 mg)	N (X100 mg)
Unmodified landfill	17.5b	16.7cb	8.3b	2.6bc	8.1b	4.6b	2.1b	9.5b
Unmodified control	14.7b	1.51cb	7.2b	2.2bc	6.7b	3.9b	2.0b	7.9b
Gravel/plastic vents trench	14.6b	15.9cb	8.9b	2.6bc	5.7b	2.1b	1.8b	9.1b
Clay/vents trench	3.3a	0.1a	1.3a	0.3a	1.2a	0.6a	0.3a	1.2a
Clay trench	11.5b	16.6cb	9.0b	2.6bc	6.4b	4.6b	2.5b	9.8b
No-clay mound	10.3b	5.3b	4.4b	2.1ab	2.0b	1.6b	0.6ab	2.7b
Clay mound	19.1b	16.6cb	7.7b	2.8c	8.0b	4.6b	2.1b	9.8b
Control mound	38.6c	26.2c	17.8c	5.4d	17.5c	11.3c	4.5c	21.3c
Control trench	11.8b	15.5cb	7.2b	2.8c	7.4b	3.6b	2.2b	8.7b

* Column means followed by different letters are significantly different from one another at P<.01.

EFFECT OF PLANTING STOCK SIZE ON SPECIES ADAPTABILITY TO LANDFILLS

In order to evaluate the effect of original size of woody vegetation at the time of planting on landfill tolerance, shoot growth on small (1-2' (30-60 cm) tall) and large (6-10' (180-300 cm) tall) replicates of five species was measured on trees in the landfill and control plots (Table 31). Shoot growth of small pin oak, green ash, sugar maple and hybrid poplar (rooted cuttings) was not statistically lower on the landfill plot than on the control. Conversely, shoot growth of the large replicates of these same four species was significantly less on the landfill than in the control plot. This relationship was reversed for one species, honey locust. The large replicates exhibited no shoot growth difference between plots; whereas, shoot growth of the small trees was significantly lower on the landfill than on the control.

TABLE 31. TOTAL SHOOT GROWTH* OF SMALL+ AND LARGE PIN OAK, GREEN ASH HONEY LOCUST, SUGAR MAPLE AND HYBRID POPLAR ON LANDFILL AND CONTROL PLOTS DURING 1978 AND 1979

Species	Size	Landfill (cm)	Control (cm)	Landfill as % control	Significance level#
Pin oak	Small	33.3	43.7	76.2	N.S.
	Large	52.0	82.5	63.0	.08
Green ash	Small	64.6	95.2	67.8	N.S.
	Large	44.3	100.1	44.2	.01
Honey locust	Small	70.6	157.0	45.0	.01
	Large	119.4	146.6	81.4	N.S.
Sugar maple	Small	23.8	34.8	68.4	N.S.
	Large	15.7	34.5	45.5	.05
Hybrid poplar	Small	203.5	219.2	92.8	N.S.
	Large	83.3	210.7	39.5	.01

* Total shoot growth=shoot growth during 1978 plus shoot growth during 1979.

\+ Six small-sized trees and ten large sized trees of each species were originally planted on each plot.

\# Comparing landfill plot mean with control plot mean. N.S.=not significant @ P<.10, number indicate significance level.

EFFECT OF BALLED AND BURLAPPED VS. BARE-ROOT CONDITION ON GROWTH OF SUGAR MAPLES

Shoot growth of balled and burlapped sugar maples on the landfill plot was similar to growth on the control plot; however, growth of bare-rooted trees was significantly lower ($P<.05$) on the landfill than on the control plot (Table 32). In addition, shoot growth of the balled and burlapped maples on the landfill plot was significantly greater than that of the bare-rooted maples; whereas, growth of the two types of trees was statistically similar on the control.

TABLE 32. MEAN SHOOT LENGTH* FOR BALLED AND BURLAPPED AND BARE-ROOTED SUGAR MAPLES ON LANDFILL AND CONTROL PLOTS

Root Treatment	Landfill 1978	Landfill 1979	Control 1978	Control 1979	Landfill as % control+ (%)
Balled and burlapped	9.2	22.3	8.2	22.1	104 N.S.
Bare-rooted	4.9	10.8	10.1	22.4	46

* Each value is the mean for six shoots measured on each of five trees.

\+ Percentage was calculated from the total shoot length computed as 1978 growth plus 1979 growth.

‡ Differences significant at $P<.01$.

EFFECTS OF IRRIGATION ON SUGAR MAPLE GROWTH

Soil Parameters

Carbon dioxide concentrations (Table 33) were significantly higher ($P<0.01$) in the landfill plot (2.1% to 8.1%) than in the control (1.2% to 1.8%) during the 1978 and 1979 growing seasons. Oxygen concentrations varied from 15.8% to 18.1% in the landfill plot and from 19.2% to 20.1% in the control, resulting in a significantly lower oxygen content in the landfill (mean from irrigated and non-irrigated areas) (17.0%) than in the control (mean from irrigated and non-irrigated areas) (19.3%). Methane was not detected in either of the plots.

Gas readings in the irrigated and non-irrigated control areas and landfill irrigated area were alike within each treatment area throughout the summer. However, within the landfill non-irrigated area, the carbon dioxide readings were consistantly higher and oxygen consistantly lower in the southern sampling point than in the northern gas sampling station.

TABLE 33. AVERAGE CARBON DIOXIDE AND OXYGEN CONCENTRATIONS IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Gas	Year	Landfill North	Landfill South	Control North	Control South
			%			
Irrigated						
	O_2	1978	17.8	17.9	19.7	19.8
		1979	18.1	17.9	20.1	20.0
		Mean	17.9		19.9	
	CO_2	1978	2.4	2.1	1.4	1.7
		1979	3.4	2.4	1.2	1.5
		Mean	2.6		1.4	
Non-Irrigated						
	O_2	1978	16.9	15.8	19.8	19.2
		1979	16.4	15.8	20.1	19.9
		Mean	16.2		19.7	
	CO_2	1978	2.8	7.6	1.8	1.3
		1979	3.4	8.1	1.3	1.4
		Mean	5.5		1.4	

* Each average was calculated from 12 readings at 20 cm (2-8 in) deep sampling locations totaling 24 readings.

Soil temperatures during the summers of 1978 and 1979 were statistically higher ($P<.01$) on the landfill irrigated (19.8°C (66.7°F)) and landfill non-irrigated (19.4°C (66.9°F)) plots than in the control (18.2°C (64.7°F) but there were no other differences (Table 34).

Soil moisture was significantly lower than in the control plot (Table 35) throughout both summers. Irrigating the landfill and control areas significantly increased soil moisture compared to the non-irrigated areas during 1978, but not during 1979. The increase was similar for both the landfill and control plots.

Soil nutrient levels in each of the four areas (Table 36) were similar for most elements except that in the control irrigated plot the calcium was considerably lower and the iron was much higher than in the other three treatment areas. The magnesium content in the control non-irrigated area was also much higher than in the other three areas.

TABLE 34. AVERAGE SOIL TEMPERATURES* IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Year	Landfill North °C	(°F)	Landfill South °C	(°F)	Control North °C	(°F)	Control South °C	(°F)
Irrigated	1978	19.[illegible]	(67.1)	19.3	(66.8)	18.2	(64.8)	18.4	(65.1)
	1979	19.0	(66.2)	19.3	(66.8)	18.4	(65.1)	17.9	(64.2)
	Mean+		19.8	(66.7)‡			18.2	(64.8)	
Non-Irrigated									
	1978	19.1	(66.4)	19.5	(67.1)	17.7	(63.9)	18.3	(64.9)
	1979	18.9	(66.1)	19.9	(67.9)	18.4	(65.2)	18.4	(65.1)
	Mean+		19.4	(66.9)‡			18.2	(64.7)	

* Each average was calculated from 12 readings at 20 cm (2-8 in) deep sampling locations totaling 24 readings.

\+ Mean computed from 96 readings.

‡ Significantly greater than control plot @ P<.01.

TABLE 35. SOIL MOISTURE* IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill		Control	
	1978	1979	1978	1979
	%			
Irrigated	9.4b+	10.1bc	11.1cd	12.0d
Non-Irrigated	7.1a	9.3b	9.8b	11.1cd
Mean	8.3	9.7	10.5	11.5

* Soil moisture on a % dry weight basis. Each value was computed from 12 moisture readings at 3 samples locations totaling 36 readings.

\+ Numbers followed by different letters are significantly different from each other @ P<.01.

TABLE 36. SOIL NUTRIENT VALUES* IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS IN OCTOBER 1978

	Landfill		Control	
	Irrigated	Non-Irrigated	Irrigated	Non-Irrigated
	(ppm)			
Nitrate Nitrogen	8	9	18	9
Ammonium Nitrogen	12	12	16	12
Phosphorus	31	19	17	12
Potassium	83	35	65	118
Magnesium	26	30	20	95
Calcium	134	267	62	267
Boron	0.63	0.58	0.50	0.47
Copper	6.5	2.5	4.5	3.5
Manganese	30.0	18.0	23.0	44.0
Iron	81.0	55.0	300.0	51.0
Zinc	10.0	3.5	3.6	6.5
Texture	Sandy Loam Loamy Sand	Sandy Loam	Sandy Loam	Sandy Loam/ Sandy Clay Loam

* Values are the mean from 2 samples taken from each plot on one sampling day in October 1978.

Tree Growth

Shoot growth of sugar maples on the control was significantly greater than on the landfill plot during 1978 and 1979 (Table 37). Growth was reduced on the non-irrigated areas of both plots, this difference was statistically significant only on the landfill in 1979. Despite the nonsignificance during 1978, the average absolute reduction in shoot growth in non-irrigated vs. irrigated areas on the landfill plot was more than twice that on the control.

TABLE 37. MEAN SHOOT LENGTH* OF SUGAR MAPLES+ IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill 1978	Landfill 1979	Control 1978	Control 1979
	cm			
Irrigated	10.2a^	20.1d	12.8b	24.6e
Non-Irrigated	9.0a	15.4c	12.4b	23.2e

* Each value was computed from measurements on 30 trees.

+ Thirty 2-year old seedling were originally planted in each of 4 areas: landfill and control irrigated and non-irrigated areas.

^ Values followed by different letters are significantly different at P<.01.

Sugar maples growing on the landfill plot produced significantly (P<.01) fewer nodes and, therefore, fewer leaves/shoot than those on the control plot (Table 38). Irrigating did not significantly increase the number of leaves/shoot on either plot.

TABLE 38. NUMBER OF NODES PER SHOOT ON SUGAR MAPLES IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill plot 1978	Landfill plot 1979	Control plot 1978	Control plot 1979
	No.			
Irrigated	3.22ab*	3.31b	3.32b	4.89c
Non-Irrigated	2.89a	3.35b	3.46b	4.72c
Mean	3.1	3.3	3.4	4.8
	3.2		4.10‡	

* Values followed by different letters are statistically different @ P<.01.

‡ Significantly greater than landfill plot @ P<.06.

Average leaf dry weight sugar maples was significantly less (P<.01) in the landfill plot than the control plot (Table 39). In addition, irrigating the landfill plot significantly increased leaf weight; whereas on the control, no significant difference was shown between the irrigated and non-irrigated areas.

TABLE 39. AVERAGE DRY WEIGHT* OF SUGAR MAPLE LEAVES IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill 1978	Landfill 1979	Control 1978	Control 1979
	g			
Irrigated	0.66b+	0.72b	0.83c	0.86c
Non-Irrigated	0.50a	0.55a	0.86c	0.87c
Mean	0.58	0.63	0.84	0.86
	0.61		0.85‡	

* Values were average for 2 leaves/tree from 30 trees/plot treatment/year.

\+ Values followed by different letters are significantly different from each other @ P<.01.

‡ Significantly greater than landfill plot @ P<.01.

Stomatal Resistance

Diffusive resistance readings were made on sugar maple leaves in the irrigated and non-irrigated landfill areas in order to evaluate the effect of soil moisture content on stomatal strategies of trees growing on landfills. Resistance measured every hour during August 18, 1978 on maples growing on the landfill plot in the irrigated area and high and low landfill gas non-irrigated areas decreased significantly and similarly between 8:30 a.m. and 10:30 a.m. (Figure 8). By 11:30 a.m. leaf resistance of trees in the high-gas (south) non-irrigated area increased sharply to the 8:30 a.m. level and fluctuated around this level for the remainder of the day. Diffusive resistance readings of leaves in the low-gas (north) non-irrigated area tended to hover close to the 11:30 a.m. reading (except for a peak at 2:30 p.m.) until the day's end when readings were close to the original early morning level. Unlike readings for the aforementioned areas, readings in the low-gas irrigated area (Figure 8) continued to decrease until 12:30 p.m. when resistance was lowest, then gradually increased through 4:30 p.m. after which resistance increased sharply. Readings for the high-gas (south) non-irrigated area were significantly higher than for the other two areas from 11:30 a.m. through 5:30 p.m. Only two points differed significantly between low-gas irrigated and low gas non-irrigated i.e. at 2:30 p.m. and 6:30 p.m. (Figure 8).

During the period from August 9 through August 23, 1978, diffusive resistance readings for sugar maple leaves were significantly increased on the landfill plot compared to the control plot (Table 40). Resistance on the

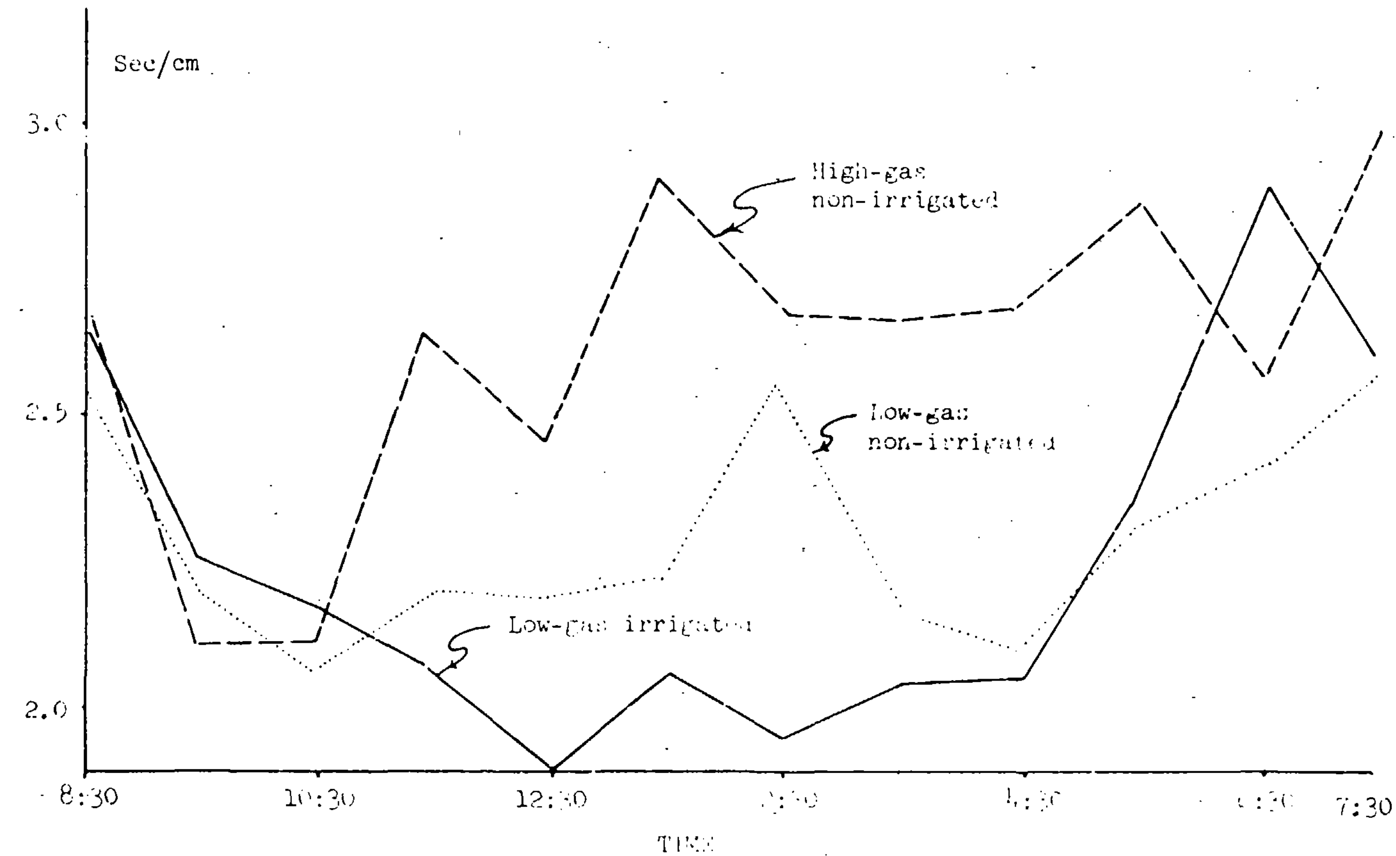

Figure 8. Stomatal resistance for sugar maples on August 1[illegible], 1978 for irrigated and non-irrigated landfill areas.

non-irrigated areas was significantly greater than the increase on the control.

TABLE 40. DIFFUSIVE RESISTANCE READINGS* FOR SUGAR MAPLE ON LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS FROM AUGUST 9 THROUGH AUGUST 23, 1978

Area	Landfill	Control
	------- sec/cm -------	
Irrigated	2.2a+	2.2a
Non-Irrigated	2.7b	2.3a
Mean	2.45‡	2.25

* Readings are average of 2 readings/tree for 5 trees in each area. Readings were taken between 10:00 a.m. and 12:00 a.m. each day.

\+ Values followed by different letters are significantly different @ P<.05.

‡ Significantly greater than control plot @ P<.01.

Effects of Soil and Meterological Parameters on Stomatal Resistance

When air temperature and relative humidity during August 18 were regressed onto diffusive resistance readings for maples in the high-gas (south) non-irrigated area (CO_2=7.8%, O_2=15.8%), no effects were statistically significant even at the P<.50 level, to justify a descriptive multiple regression model. However, in the low-gas non-irrigated area (CO_2=2.3%, O_2=16.0%) 16% of the variability of diffusive resistance readings could be accounted for in the model:

$$D = 80.4 - 13.1 \, Log_N(T_A). \quad eq\ 1,\ R^2 = 16\%$$

where:
- D = Diffusive Resistance
- T_A = Air Temperature, °F
- Log_N = Natural Logarithum

While this model did not account for much of the variability in diffusive resistance readings, the model describing variability in readings for the low-gas irrigated area (CO_2=2.3%, O_2=17.9%):

$$D = 1271.0 - 21.3\,(T_A) + 0.1\,(T_A)^2 - 131.5\,Log_{10}\,(R) \quad eq\ 2$$

where:
- D = Diffusive Resistance
- T_A = Air Temperature, °F
- R = % Relative Humidity

accounted for 71% of the variability.

Regression of the independent variables: soil gas, soil moisture and meteorological data from August 9 through August 23 onto diffusive resistance of sugar maple leaves was performed for the irrigated and non-irrigated areas on both plots. Variation of resistance readings from day to day in both the control irrigated and non-irrigated areas was correlated with changes in total wind movement from day to day according to the models:

For control irrigated

$$D = 12.4 + \frac{222.3}{wind} \qquad R^2=43\%,\ P<.05 \quad \text{eq 3}$$

where:
D = Diffusive Resistance

For control non-irrigated

$$D = 14.6 + \frac{211.6}{wind} \qquad R^2=53\%,\ P<.01 \quad \text{eq 4}$$

where:
D = Diffusive Resistance

When untransformed linear values of the independent variables were used in the regression on the landfill plot, air temperature was positively correlated with resistance readings on the irrigated area (R^2=19%), whereas, oxygen was negatively correlated (R^2=62%) with readings on the non-irrigated area where the oxygen content varied significantly more than in all other areas.

When reciprocal and quadratic effects were added to the regression, resistance readings for maples on the landfill plot were correlated with moisture content and oxygen:

For experimental irrigated

$$D = 32.4 + 0.9\,(M.C.)^2 - 3.1\,(M.C.)^{3/2} \quad R^2 = 64\%\ P<.03$$

For experimental non-irrigated

$$D = -13.0 + 474.1/O_2 \qquad R^2=72\%\ P<.01$$

where:
D = Diffusive Resistance
M.C. = Moisture Content
O_2 = Oxygen concentration

EFFECTS OF THE SOIL ENVIRONMENT IN SIX TREATMENT AREAS ON ROOT DISTRIBUTION OF AMERICAN BASSWOOD

In the clay/vents trench where the CO_2, O_2 and CH_4 concentrations averaged 22.8%, 4.3% and 12.0% respectively (Table 41) throughout the 1977 growing season, total root length averages 241 cm. Conversely, in the gravel, plastic/vents trench, the CO_2 concentration averaged 1.4%; O_2, 19.8%; CH_4, 0.1%, and total root length was 1676 cm. The concentration of landfill gas (CO_2 and CH_4) present in the soil atmospheres was negatively correlated (r=0.69 and -0.52 respectively), whereas oxygen was positively correlated (r=+0.72) with total root length. Multiple regression analysis of total root length produced the following equation: Total Root Length (cm) = 3132.3 - 110.3 CO_2 + 112.9 O_2 with an R^2 = .47.

TABLE 41. ROOT LENGTH, AVERAGE AND MAXIMUM DEPTH, AND FREQUENCY OF ROOT GROWTH DIRECTION CLASS FOR AMERICAN BASSWOOD; * SOIL CARBON DIOXIDE, METHANE AND OXYGEN CONCENTRATIONS+ IN EACH AREA

	Trench area					
Parameter	Unmodified landfill area	Unmodified control area	Gravel plastic vents trench	Clay vents trench	Clay trench	Control trench
Total root length (cm)	789b[Δ]	2204c	1676c	241a	1922c	1762c
Average root depth (cm)	7.4a	20.8b	24.4b	18.0b	18.3b	18.8c
Maximum root depth (cm)	15.1a	71.1b	81.3b	20.3a	60.9b	81.3b
% of total root length which grew downward	9.5	46.8	51.6	0.0	32.4	53.0
% of total root length which grew up toward soil surface	66.7	38.9	35.5	68.3	59.5	41.7
% of total root length which grew parallel to soil surface	23.8	14.3	12.9	31.7	8.1	5.3
% O_2	18.5a	19.5a	19.8a	4.3b	17.2c	19.6a
% CO_2	8.1b	1.0a	1.4a	22.8c	5.8b	1.2a
% CH_4	0.9 b	0.0a	0.1a	12.0c	0.1a	0.0a

* Each value is the mean for two trees.

\+ Each value is the mean of 12 readings at 30 cm soil depth throughout the growing season. Concentrations are in % by volume.

Δ Values followed by different letters are significantly different at P<.05.

Average root depth in each area is presented in Table 41. Roots in the unmodified landfill area had a significantly shallower depth than in all other areas. The maximum depth of root penetration in the clay/vents trench and unmodified landfill areas was a third of that in other areas. Results of Chi-Square Analysis showed that there was a significant relationship between distribution of root growth and the six trench areas (Table 41). Subdividing the Chi-Square Analysis shows that the distribution of roots in the root growth-direction classes in the unmodified landfill area and the clay/vents trench, was significantly different from that in the remaining four areas. In these two areas, the CO_2 and CH_4 concentrations were considerably higher in all other treatments.

The frequency distribution differences among areas were particularly pronounced in the "percentage downward root growth" row of Table 41 where the trees in the unmodified landfill and clay/vents trench areas locate 9.5 or 0% of their roots, respectively, compared to 32.4% or more for all other treatments. There appear to be two treatment groups in the "percentage upward root growth" row: one consisting of unmodified landfill area, clay/vents trench, and clay trench where the soil CO_2 content ranged from 5.8 to 22.8%; and another consisting of unmodified control area, gravel/plastic/vents trench and control trench where the soil CO_2 content ranged from 1.0 to 1.4%. In the first group (high CO_2) 59.5% or more of the roots grew toward the soil surface, whereas, fewer than 41.7% grew upward in the latter group (low CO_2).

Chi-Square Analysis of root depth class versus treatment area indicated a dependency between the frequency of roots in each depth class and the six treatment areas (Table 42). Upon subdividing the analysis, the frequency distribution in the unmodified landfill area and clay/vents trench was found to be different than in all other areas i.e. all roots were growing in the top 23 cm of soil in these two treatment areas. On the other hand, in all other areas, some roots penetrated at least to 46 cm below the soil surface. The frequency distributions of roots in the gravel/plastic/vents trench, clay trench, control trench, and unmodified control areas were not significantly different ($P<.05$) from each other.

EFFECTS OF LANDFILL SOIL ENVIRONMENT ON ROOT DISTRIBUTION OF FIVE WOODY SPECIES

Mean root depth and total root length (roots with diameter of 1 mm or more) for five species on the landfill and control plots are presented in Table 43. Mean root depth for Japanese black pine, and hybrid poplar saplings and rooted cuttings, honey locust and green ash saplings was less on the landfill plot than on the control plot. Norway spruce was the only species with a root system that was deeper on the landfill plot than on the control. Root length for Norway spruce and Japanese black pine was also slightly greater on the landfill than on the control area. Root length for the remaining three species was less on the landfill than on the control (Table 43).

The percentage of roots at each soil depth is given in Figures 9 through 15 for the five species excavated for extensive root study. In root depth classes of 10.1 cm or greater, the bar represents the average percentage for

TABLE 42. PERCENTAGE OF ROOTS IN EACH ROOT-DEPTH CLASS FOR EACH TRENCH AREA

Root-depth class (cm)	Unmodified landfill area	Unmodified control area	Trench Area Gravel plastic vents trench	Clay vents trench	Clay trench	Control trench
	%					
0- 8.0	71.4a‡	23.8c	25.8c	0.0b	24.3c	19.2c
> 8.0-15.0	28.6	25.7	22.5	33.3	24.3	27.2
> 15.0-23.0	0.0	20.7	6.5	66.7	21.6	24.9
> 23.0-30.0	0.0	14.8	9.7	0.0	13.5	17.9
> 30.0-38.0	0.0	3.9	3.2	0.0	5.4	5.4
> 38.0-45.0	0.0	5.6	12.9	0.0	5.4	2.7
> 45.0-53.0	0.0	5.5	16.1	0.0	5.4	2.7
below 53.1	0.0	0.0	3.3	0.0	0.0	0.0

‡ Columns with similar letters have similar distribution by Chi-square analysis @ P <.05.

TABLE 43. MEAN ROOT DEPTH* AND TOTAL ROOT LENGTH* FOR SEVERAL SPECIES ON LANDFILL AND CONTROL PLOTS

Species+	Landfill		Control		Landfill as % of control	
	Depth (cm)	Length (m)	Depth (cm)	Length (m)	Depth (cm)	Length (m)
Japanese black pine	7.8	25.4	9.3	23.0	83.9	106.5
Norway spruce	5.1	28.6	4.2	26.2	121.4	109.2
Hybrid poplar (rooted cuttings)	6.3	90.8	13.6	113.5	46.3	80.0
Honey locust	8.3	16.9	16.6	53.0	50.0	31.9
Green ash (saplings)	9.3	44.9	14.7	94.3	63.4	47.6
Hybrid poplar (saplings)	8.5	35.9	12.8	97.5	66.4	36.8

* Each value is the mean of 2 replicates.

\+ Species are arranged from most to least tolerant of landfill conditions according to Table 12.

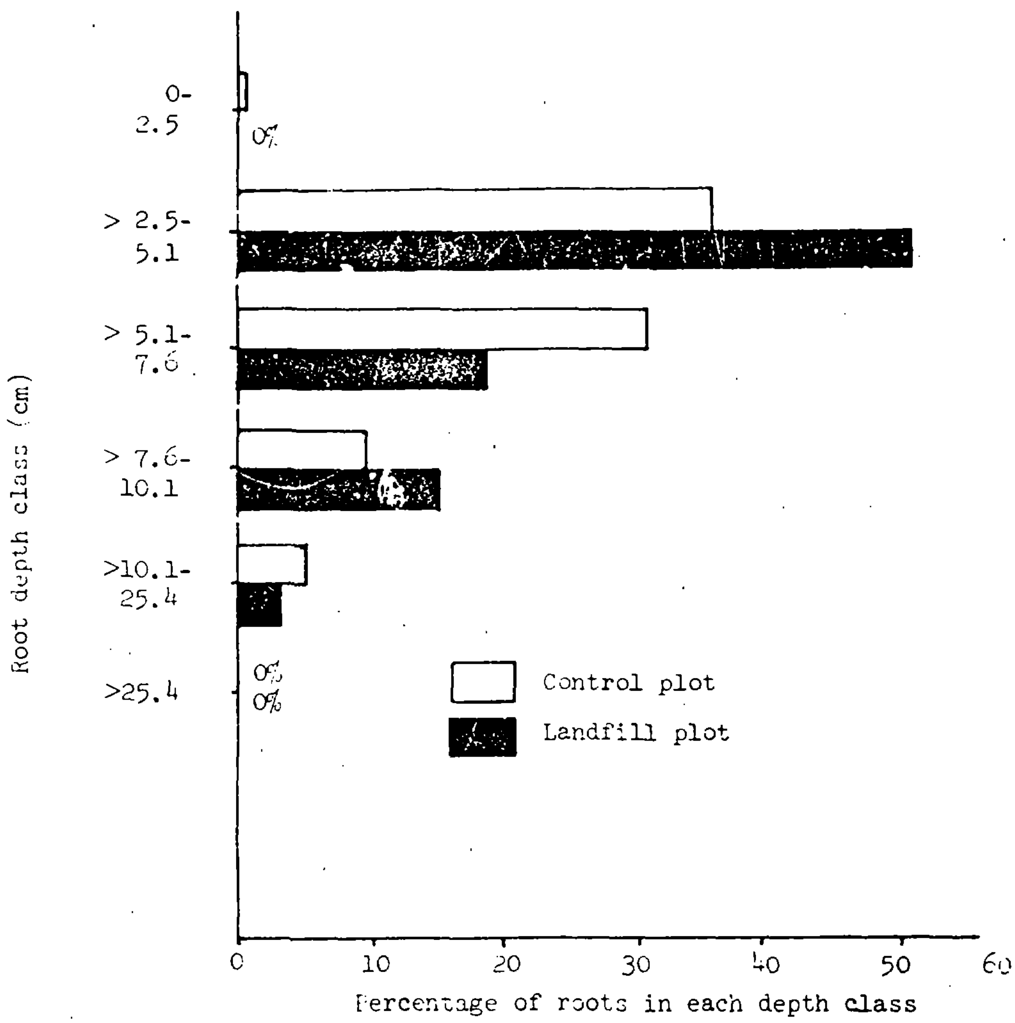

Figure 9. Vertical root distribution of Japanese black pine in landfill and control plots. Each is the mean for two trees.

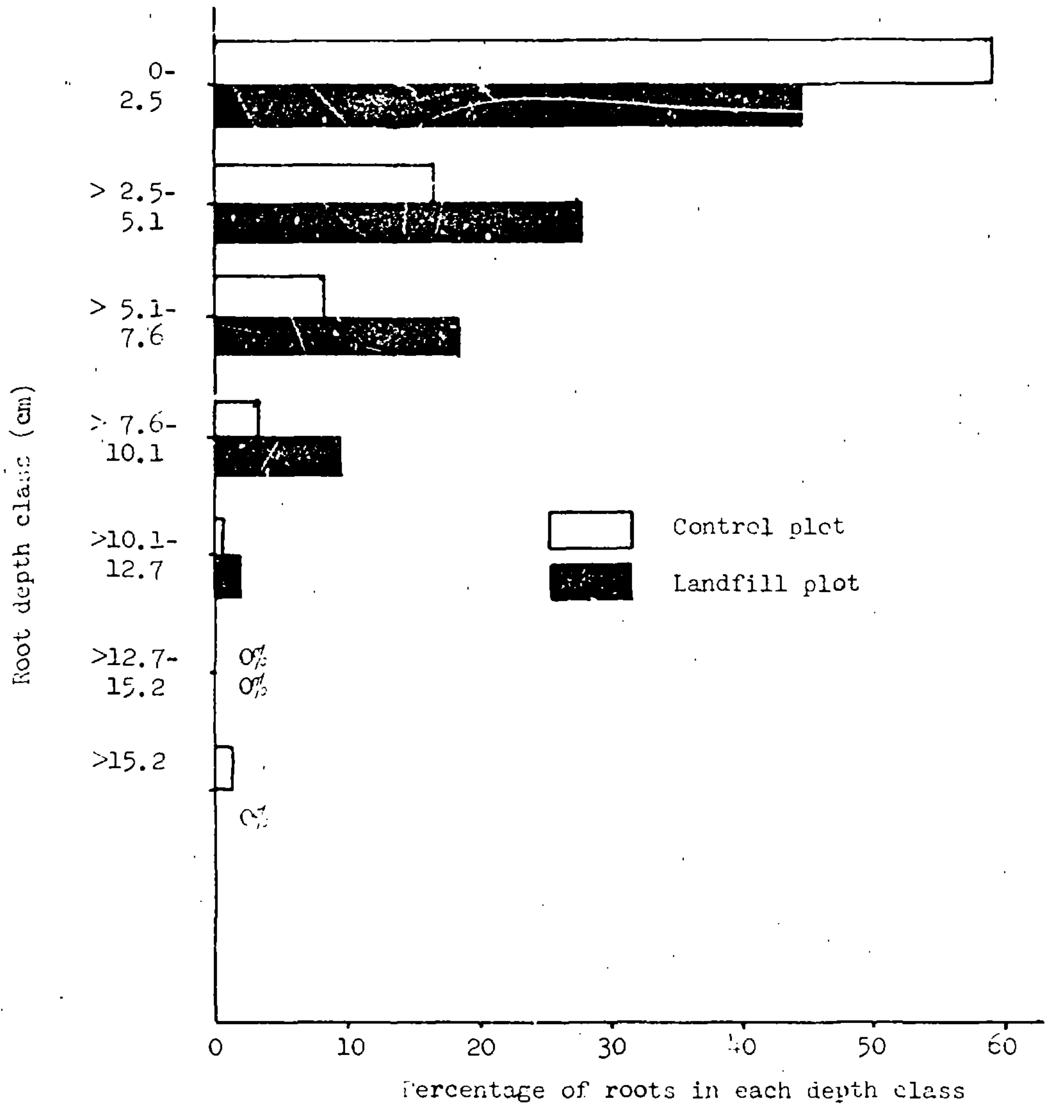

Figure 10. Vertical root distribution of Norway spruce in landfill and control plots. Each value is the mean for two trees.

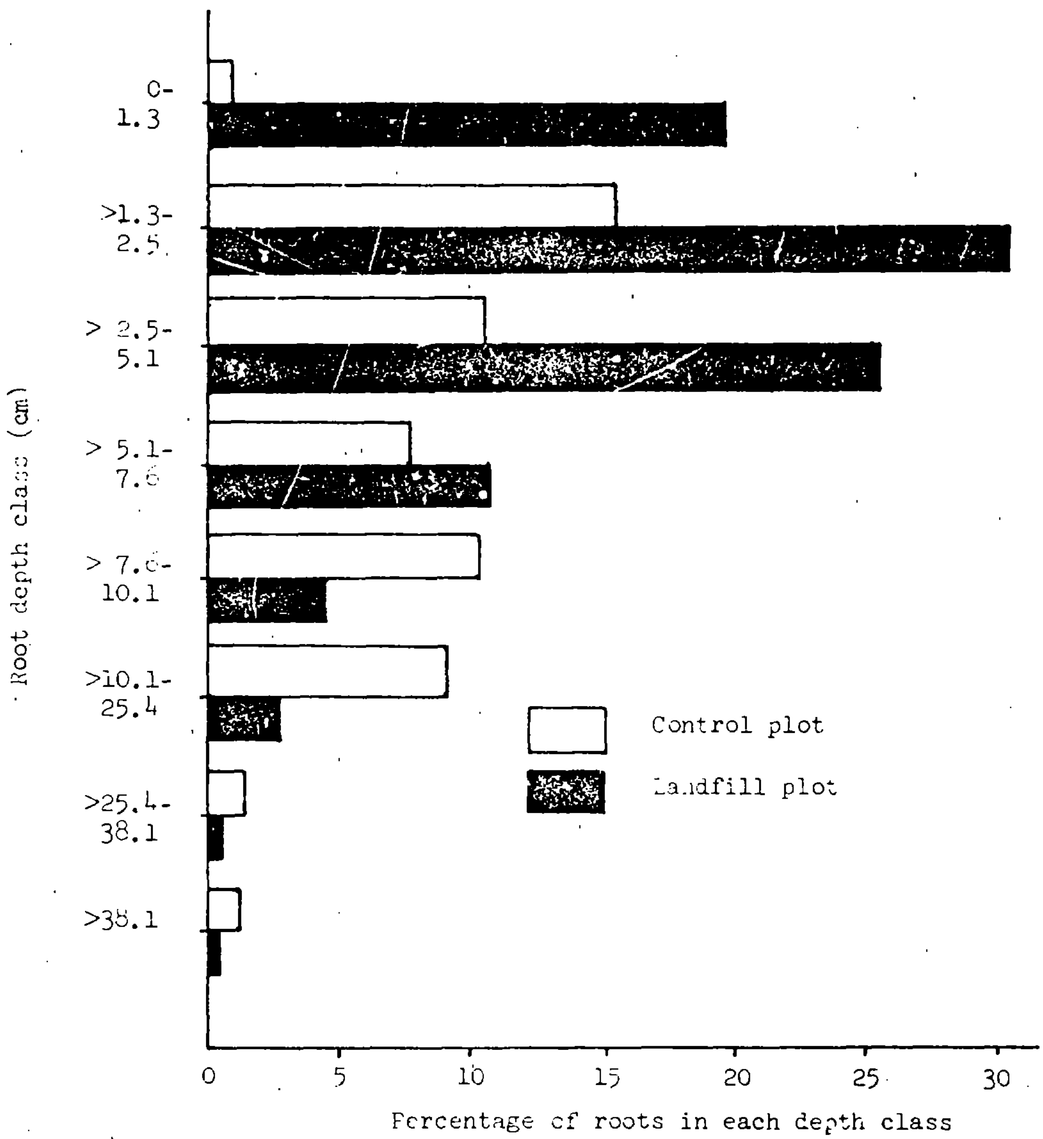

Figure 11. Vertical root distribution of hybrid poplar cuttings in landfill and control plots. Each value is the mean for two trees.

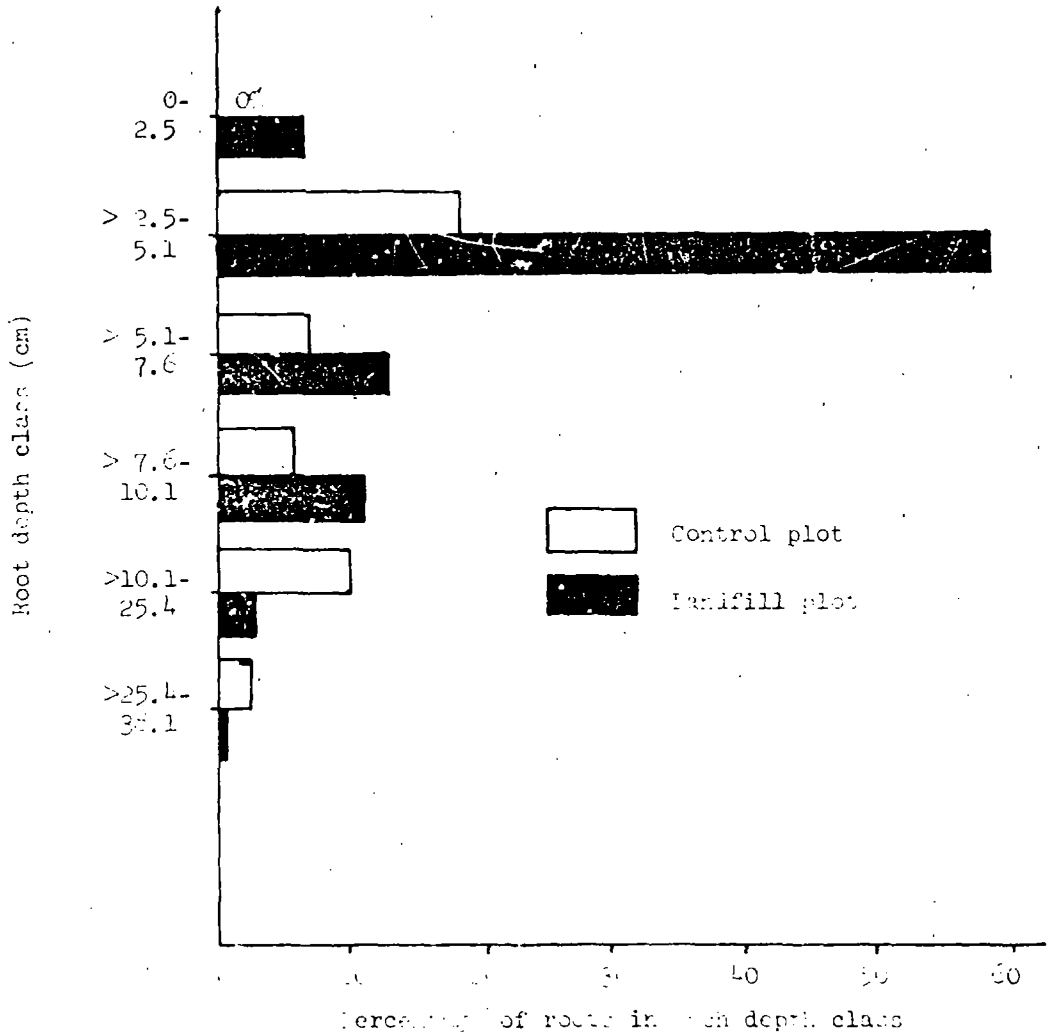

Figure 12. Vertical root distribution of honey locust in landfill and control plots. Each value is the mean for two trees.

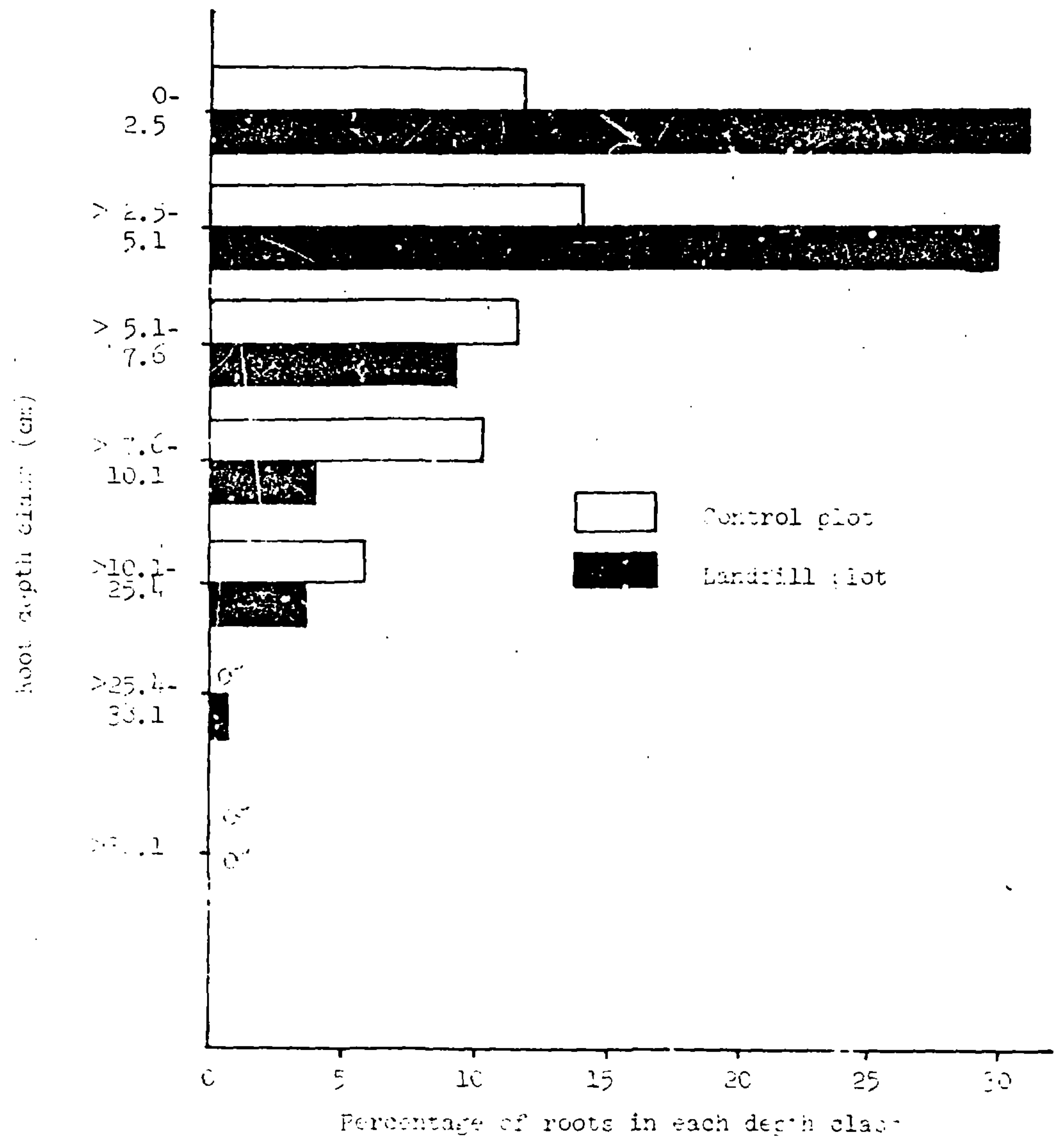

Figure 13. Vertical root distribution of green ash in landfill and control plots. Each value is the mean for two trees.

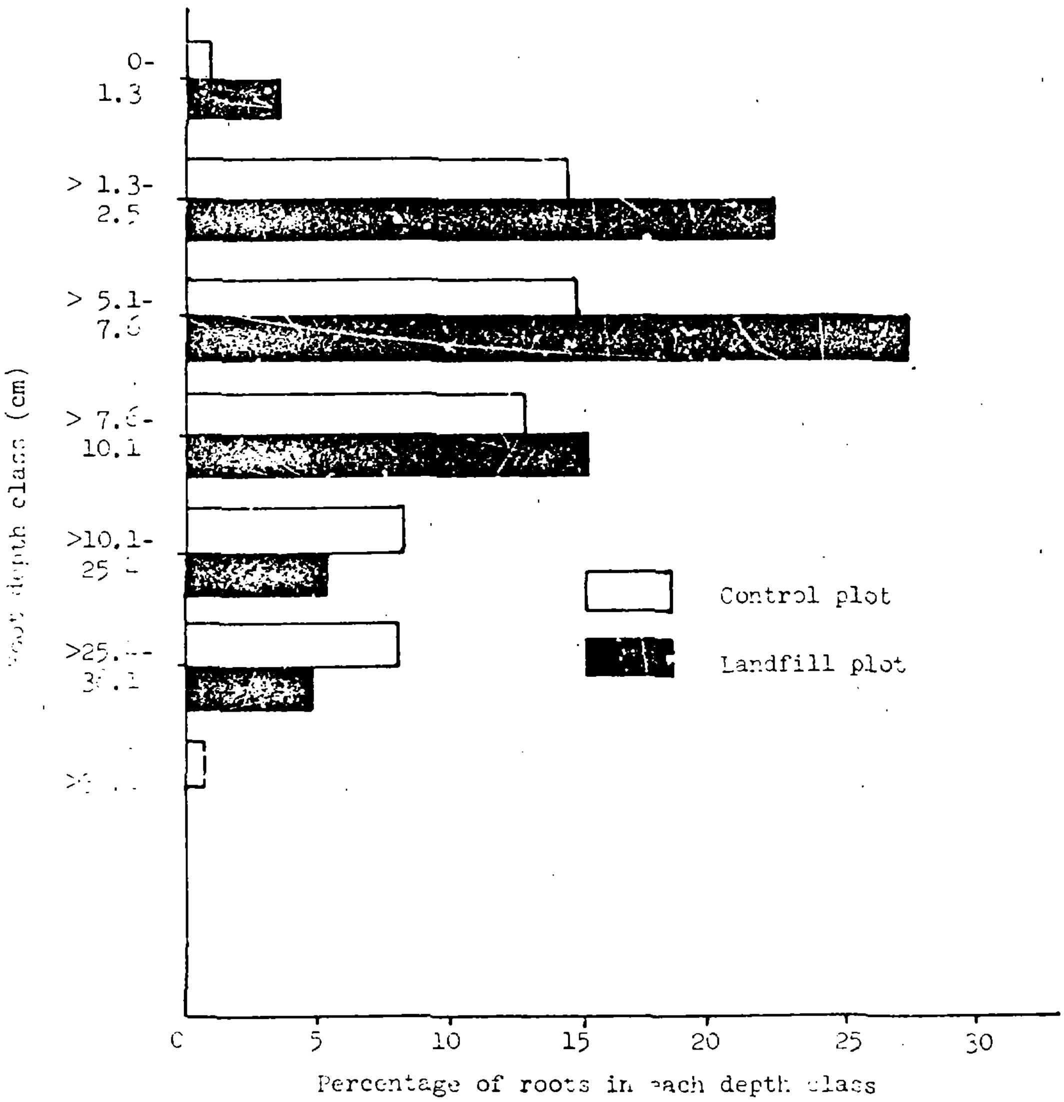

Figure 1-. Vertical root distribution of hybrid poplar in landfill and control plots. Each value is the mean for two trees.

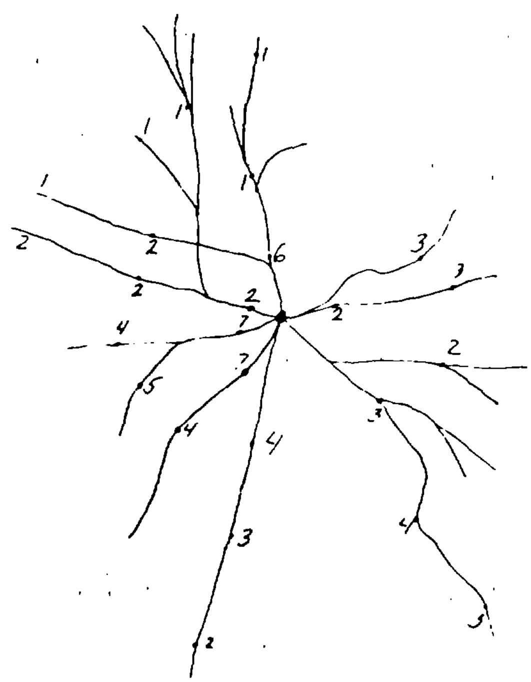

Figure 26. Diagram of green ash seedling B root system in landfill plot indicating root depth in inches at 30.5-cm (12-in) intervals.

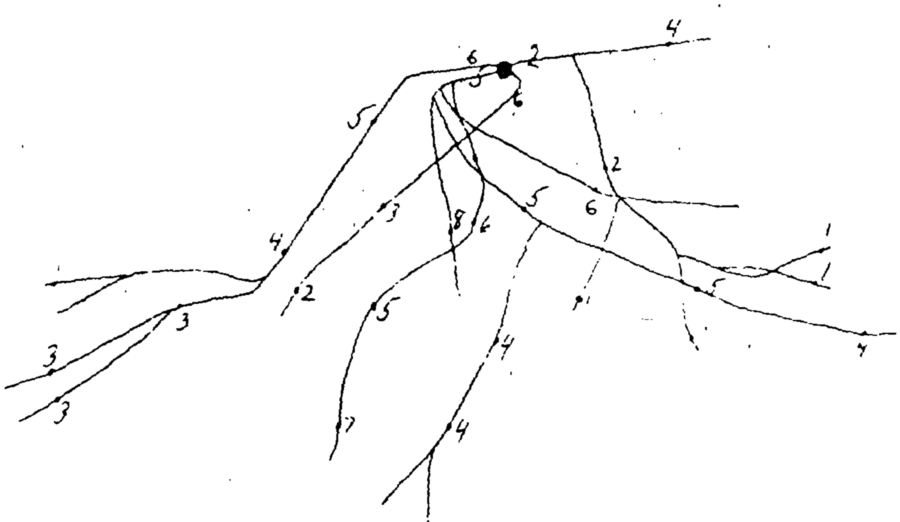

Figure 25. Diagram of green ash seedling A root system in landfill plot indicating root depth in inches at 30.5-cm (12-in) intervals.

control plot.

TABLE 46. MEAN ROOT DEPTH AND TOTAL ROOT LENGTH FOR HYBRID POPLAR CUTTINGS ON LANDFILL AND CONTROL PLOTS

Location	Average Root depth (cm)	Total Root length (m)
Landfill Plot*		
Low-gas area	8.9	96.0
High-gas area	3.8	85.6
Control Plot+		
Area A	14.5	120.1
Area B	12.7	107.0

* Carbon dioxide averaged 18.1% at the 20 cm (8 in) depth in the high-gas area and 1.4% at the 20 cm (8 in) depth in the low-gas area from 1976 through 1979.

\+ Carbon dioxide averaged 1.1% at the 20 cm (8 in) depth from 1976 through 1979.

Root systems of the four excavated green ash seedlings (2 years old when planted) are diagrammed in Figures 25 through 28. Green ash seedling A (Figure 25) on the landfill plot was growing in an area where the carbon dioxide averaged 5.2%, methane averaged 1.9% and oxygen averaged 19.8% during 1977, 1978 and 1979. The other excavated landfill tree (B) (Figure 26) was growing in an area where the carbon dioxide concentration averaged 14.7%, methane 6.1% and oxygen 16.1%. Carbon dioxide averaged 1.1%, oxygen averaged 19.8% and methane was never detected in the control plot.

The roots of green ash B growing in the high-gas landfill area were concentrated near the soil surface (Table 47) and (Figure 29C), whereas roots of ash A growing in a low-gas landfill area (Figure 29B) penetrated to slightly deeper depths (Table 47). On the other hand, few roots on control trees were found in the top 10.1 cm (4 in).

A close-up photograph of the lower portion of the ash root system in the low-gas landfill area (Figure 30B) depicts an abundance of short roots at about the 20-cm (8-in) depth. The soil immediately below this short root zone was darker than the surrounding soil and was giving off a septic odor. No odor was detected in the soil above this point. Short root formation was not as noticeable on the ash growing in the high-gas area on the landfill (Figure 30A).

Root depth and length values for ash growing in both the high and low landfill gas areas were approximately half the values of the control (Table 48). There was little difference in depth and length between the two trees

Figure 24. Close-up of hybrid poplar cutting root system on control plot.

Figure 23. Root system of hybrid poplar cuttings on control plot.

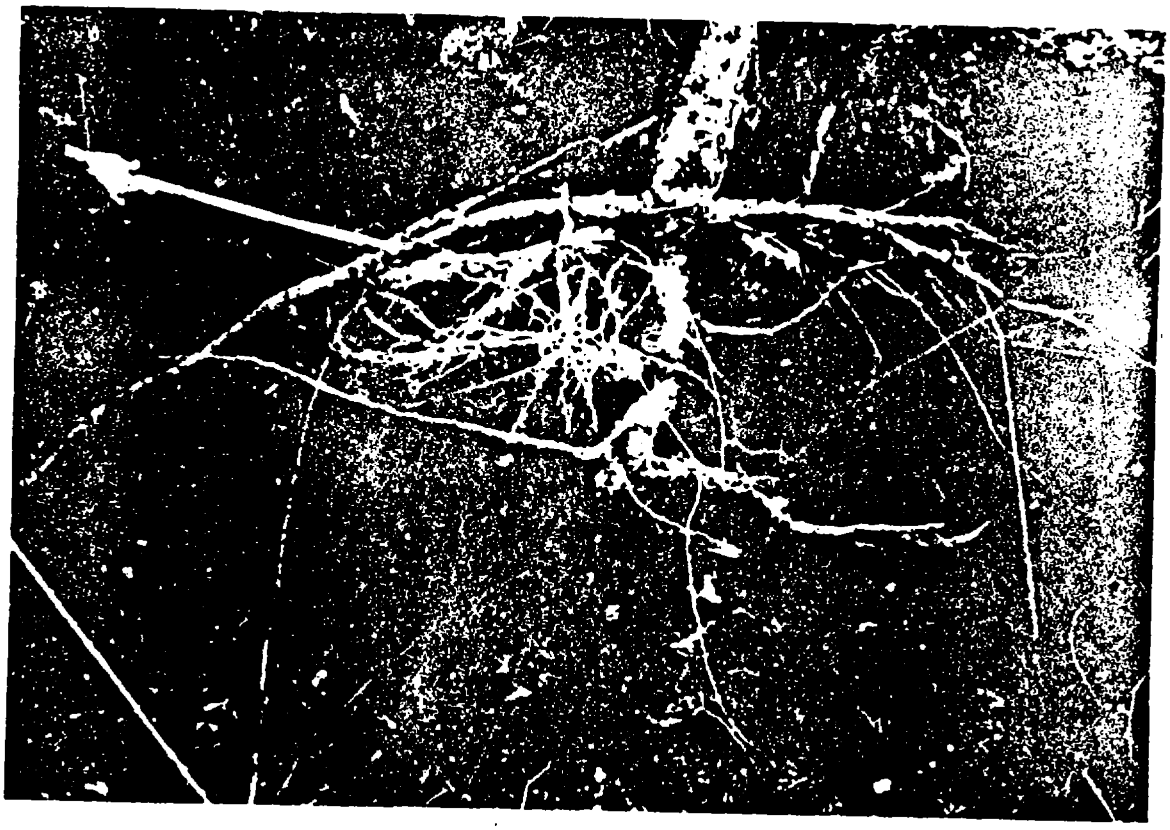

Figure 22. Root system of hybrid poplar cutting in low-gas landfill area.

Figure 21. Surface roots of hybrid poplar in high-gas area on landfill plot.

TABLE 45. PERCENTAGE OF ROOTS OF HYBRID POPLAR CUTTINGS IN EACH ROOT-DEPTH CLASS IN HIGH AND LOW GAS* AREAS

Root depth class	Landfill High gas Area B	Landfill Low gas Area A	Control Area A	Control Area B
	%			
0- 1.3	34.9a+	3.8b	0c	1.4c
1.3- 5.1	43.5	67.6	18.4	36.1
5.1-10.1	16.8	12.9	15.8	20.2
10.1-25.4	4.7	11.3	45.1	27.5
25.4-38.1	0	1.6	7.9	6.9
38.1-50.8	0	2.0	4.0	2.1
50.8	0	0.9	0.3	1.4

* See Table 44 for gas concentrations.

\+ Columns with similar letters have similar root distributions at P<.01 by Chi-Square Analysis.

The arrow in Figure 21 A points to a surface root approximately 4 m (13 ft) long growing from the poplar in the high-gas area. This root originated at the 5 cm (2 in) depth and grew upward to the 2.5-cm (1 in) depth within 60 cm (24 in) of the stump and continued to elongate at this depth for approximately 3.5 m (11.5 ft). The extent of root development in the top several cm of soil in the high-gas area is exhibited in Figure 21B. Few roots in the top several cm of soil produced a sinker root; when a root reached the top several cm of soil, it generally remained at that depth and rarely branched to produce a root which grew toward the refuse.

The roots of the poplar cutting in the low-gas landfill area which penetrated to the 40-cm (16-in) depth (Table 44) are identified with arrows in Figure 22. Several other roots penetrating to soil depths greater than 50 cm (20 in) are not shown in this photograph, but are represented diagrammatically in Figure 16.

Roots of the two hybrid poplar (cuttings) trees in the control plot were more evenly distributed in the soil than those in the landfill plot; they were not as concentrated in the top soil layers as those in the landfill plot (Table 44). Figure 23 illustrates the root distribution around a hybrid poplar cutting on the control plot. The arrow in Figure 23 points to a root which is enlarged and marked with a large dot in Figure 24. The roots pictured here have grown from the soil surface straight down to approximately 50 cm (16 in). (The scale of the ruler in the photograph (Figure 24) is in inches.) Several of these roots (arrows) have become grafted to each other.

Average poplar root depth in the high-gas area (Table 46) was considerably shallower (3.8 cm, 1.5 in) than in the low-gas area (8.9 cm, 3.5 in) and both these areas had much shallower roots (significant @ P<.01) than the control plot. Total root length in the landfill plot was less than in the

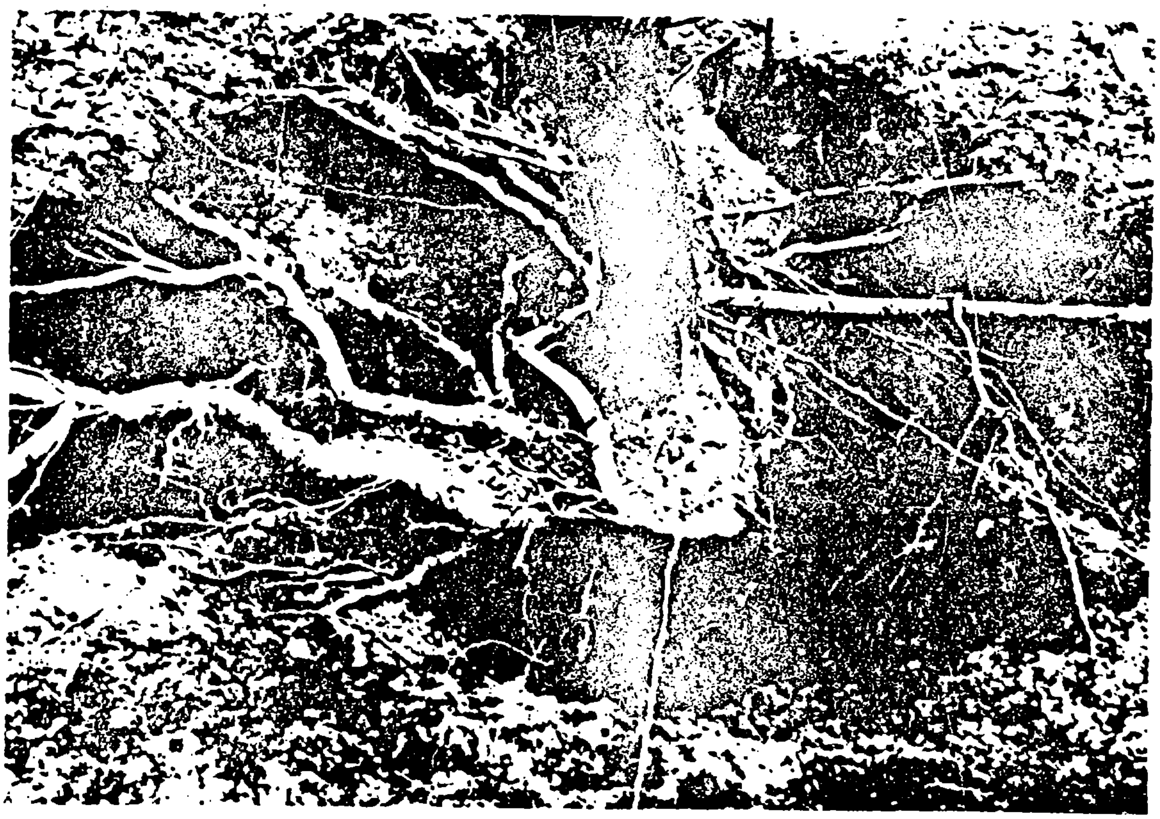

Figure 20. Root system of hybrid poplar cuttings in high gas landfill area.

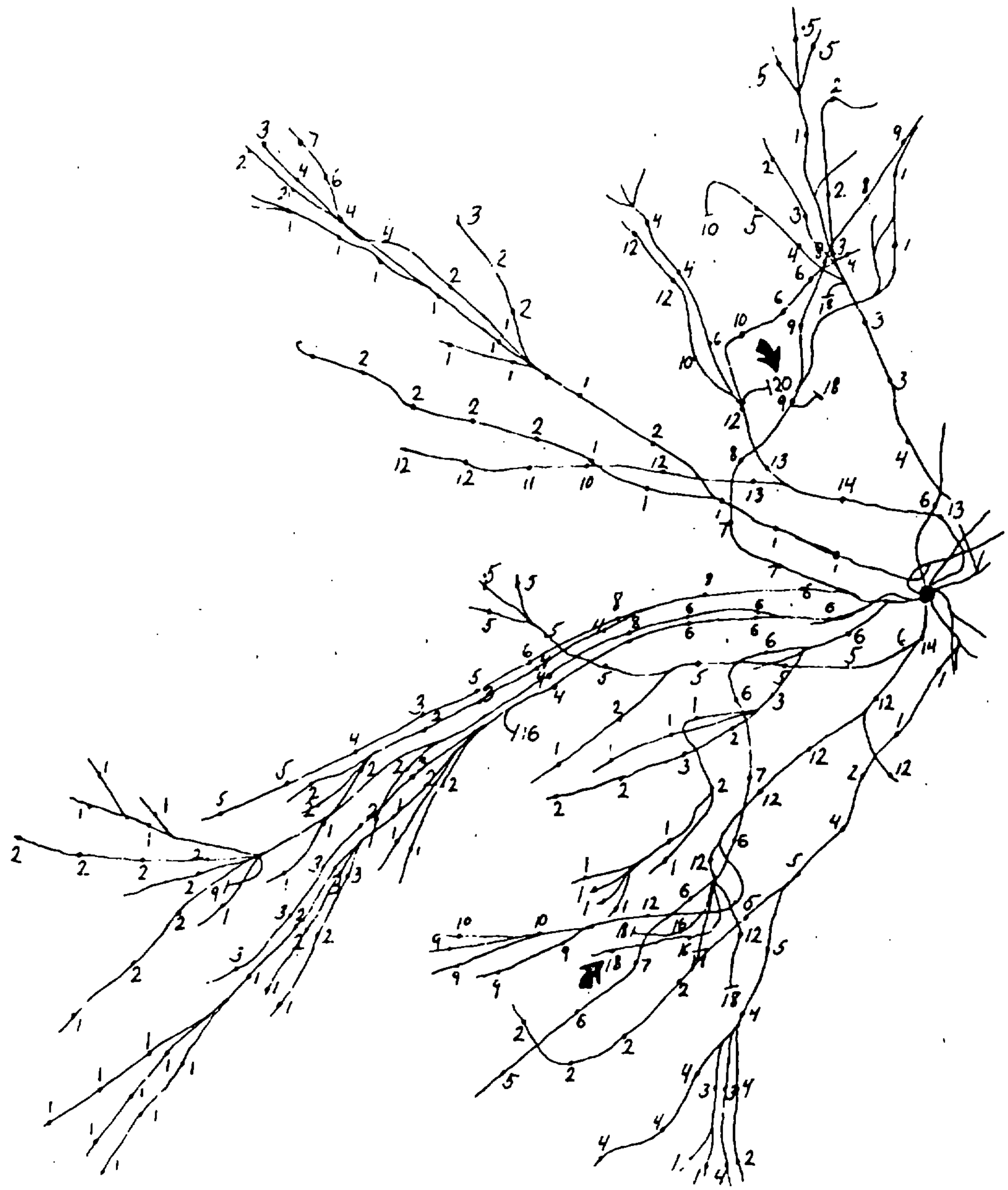

Figure 19. (continued)

Figure 19. Diagram of hybrid poplar cutting B root system in control plot indicating root depth in inches at 30.5-cm (12-in) intervals. (continued)

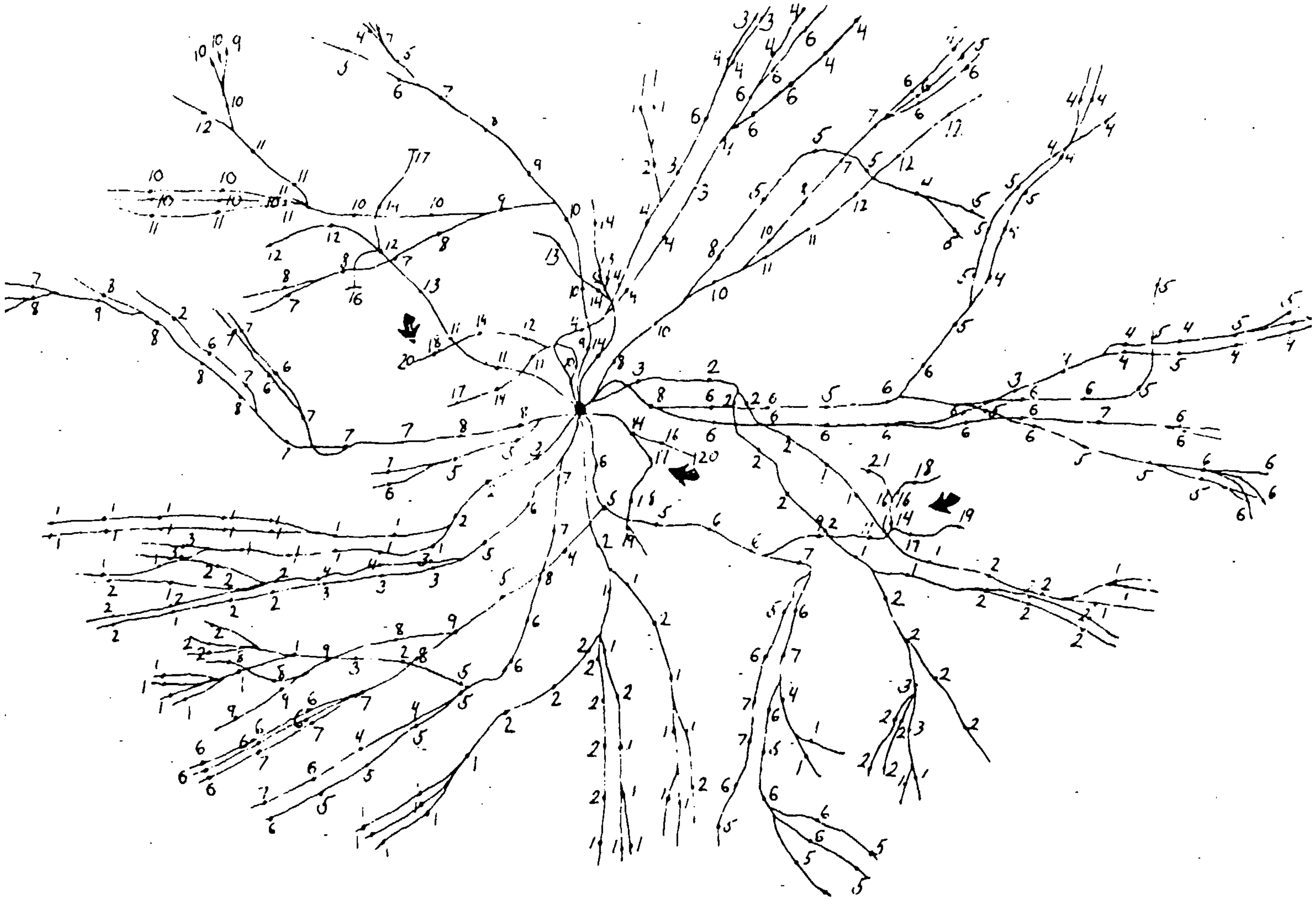

Figure 18. Diagram of hybrid poplar cutting A root system in control plot indicating root depth in inches at 30.5-cm (12-in) intervals.

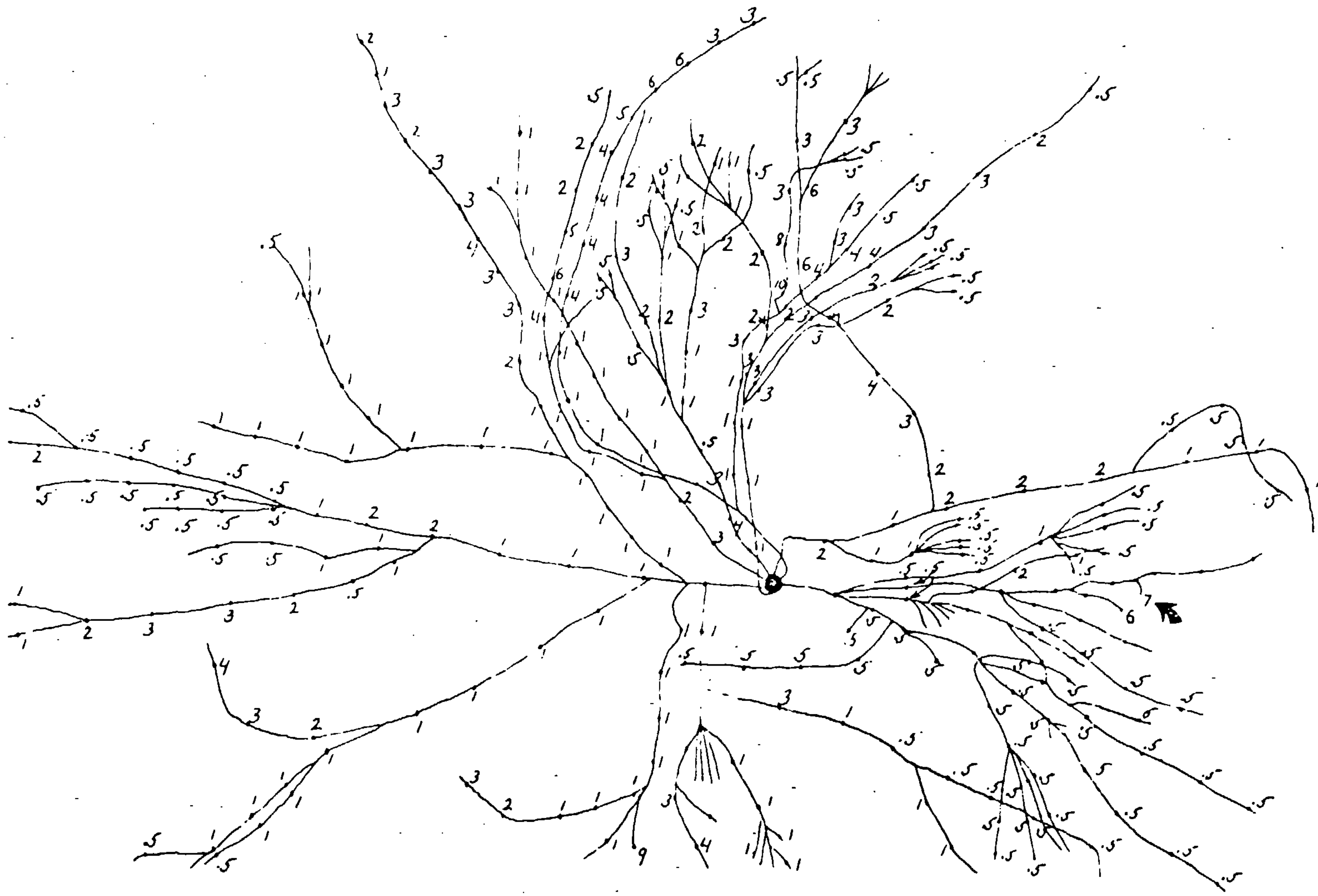

Figure 17. Diagram of hybrid poplar cutting B (high-gas) root system in landfill plot indicating root depth in inches at 30.5-cm (12-in) intervals.

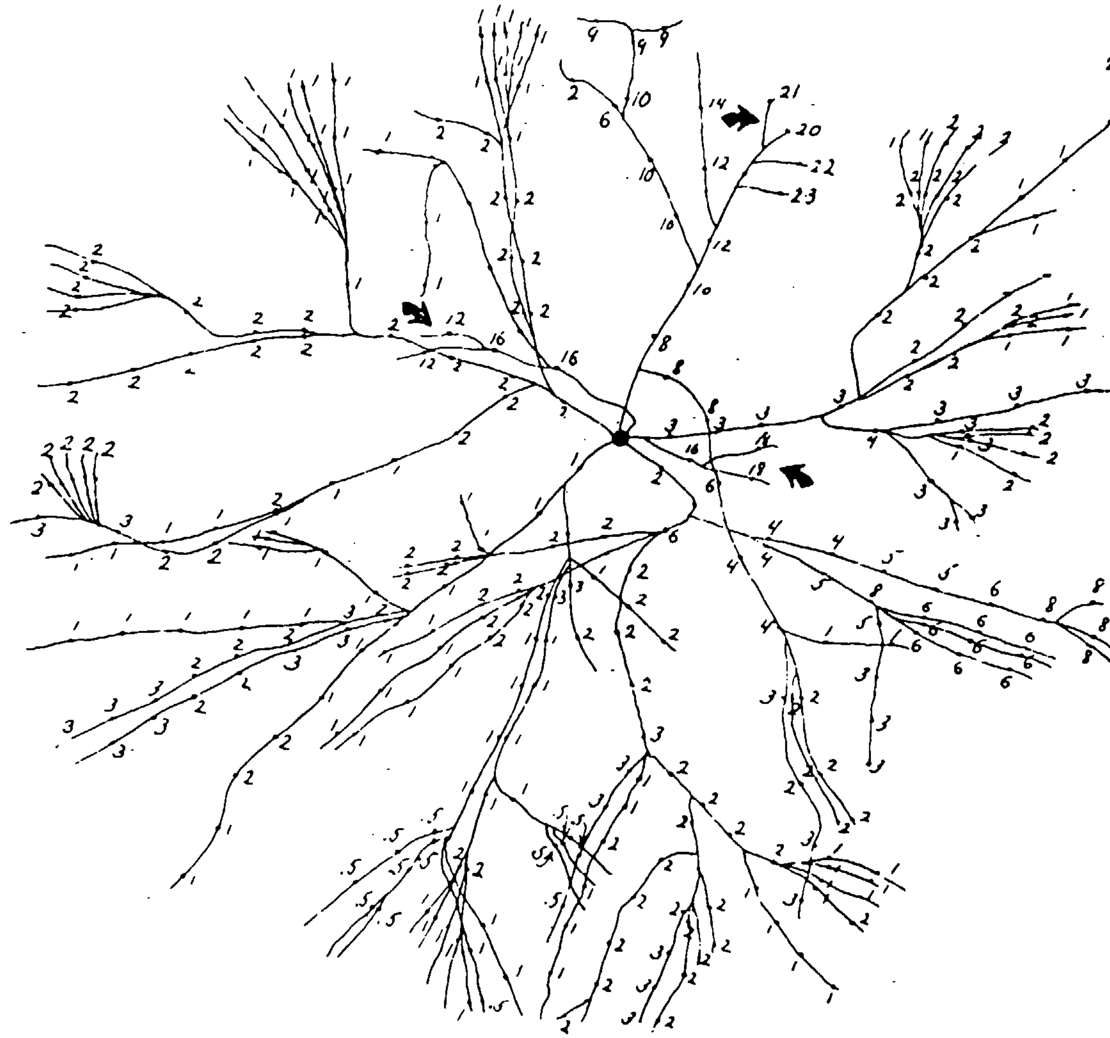

Figure 16. Diagram of hybrid poplar cutting A (low-gas) root system in landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

TABLE 44. NUMBER OF 30.5 cm (12 IN) HYBRID POPLAR (ROOTED CUTTINGS) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO_2, CH_4 AND O_2 CONCENTRATIONS AT THE 20 cm DEPTH ON LANDFILL AND CONTROL PLOTS.

		Landfill				Control			
		Tree A (low gas)		Tree B (high gas)		Tree A		Tree B	
Soil depth in	cm	# of root sections	%	# of root sections	%	# of root sections	%	# of root sections	%
0.5	1.3	12	3.8a+	98	34.9b	0	0c	5	1.4c
1	2.5	92	29.9	82	29.2	56	12.7	69	19.6
2	5.1	120	37.7	40	14.3	50	5.7	58	16.5
3	7.6	35	11.0	29	10.3	22	5.7	32	9.1
4	10.1	6	1.9	18	6.5	40	10.1	39	11.1
5	12.7	4	1.3	4	1.4	49	12.4	37	10.5
6	15.2	13	4.1	6	2.1	55	13.9	39	11.1
7	17.8	0	0	1	0.3	29	7.4	7	2.0
8	20.3	10	3.1	1	0.3	19	4.8	9	2.6
9	22.8	5	1.5	1	0.3	11	2.8	8	2.3
10	25.4	4	1.3	1	0.3	15	3.8	8	2.3
11	27.9	0	0	0	0	14	3.5	2	0.6
12	30.5	4	1.3	0	0	7	1.8	9	2.6
13	33.0	0	0	0	0	3	0.8	8	2.3
14	35.6	1	0.3	0	0	7	1.8	5	1.4
15	38.1	0	0	0	0	0	0	0	0
16	40.6	3	1.0	0	0	4	1.0	6	1.7
17	43.2	0	0	0	0	4	1.0	0	0
18	45.7	2	0.7	0	0	3	0.7	3	0.8
19	48.3	0	0	0	0	2	0.5	0	0
20	50.8	1	0.3	0	0	3	0.8	2	0.6
21	53.3	1	0.3	0	0	1	0.3	0	0
22	55.9	1	0.3	0	0	0	0	0	0
23	58.4	1	0.3	0	0	0	0	5	1.4
Total length (m)		96.0		85.6		120.1		107.0	
Mean depth (cm)		8.9		3.8		14.5		12.7	
Maximum depth (cm)		58.4		25.4		53.3		58.4	
CO_2		1.4		18.1		1.2		1.2	
CH_4		trace		5.0		0.0		0.0	
O_2		19.6		15.8		19.4		19.3	

\+ Columns with similar letters have a similar root distribution by Chi-Square Analysis at P<.01.

five-2.54 cm intervals; e.g. in order to calculate the total percentage of roots in the >25.4 cm class, multiply the bar value times five. All but one of the five species (i.e. Norway spruce) produced proportionally more roots in the upper soil layers on the landfill plot than on the control. Norway spruce on the other hand, produced approximately 58% of its root system in the top 2.5 cm of the soil; whereas, only 44% were growing at this depth in the landfill plot. More roots penetrated the deeper soil layers in the control area than in the landfill area.

The number and percentage of hybrid poplar roots at each soil depth are presented in Table 44. One of the landfill trees (Tree B, Figure 16) was located in a high-gas area where the carbon dioxide concentration during 1977, 1978 and 1979 averaged 18.1%, methane averaged 5% and oxygen averaged 15.8%. The other hybrid poplar on the landfill (Figure 17) was growing in a low-gas area where the carbon dioxide (1.4%), methane (trace) and oxygen (19.6%) concentrations were similar to concentrations around trees (Figures 18-19) in the control plot.

Root distribution of hybrid poplar cuttings in the high-gas area was significantly different from that in the low-gas landfill and control areas (Table 45). Thirty-five percent of the roots in the high-gas area were in the top 1.3 cm (0.5 in) of soil, whereas, only 3.8% were growing at this depth in the low-gas area. Less than 1.5% of the roots of the hybrid poplar in the control area were found at the 1.3 cm (0.5 in) depth. No roots were found below 25.4 cm (10 in) in the high-gas landfill area; whereas, 4.5% of the roots in the low-gas landfill area and more than 10% of the roots in the control area were found below this depth.

The black arrows in Figure 16 indicate several roots which extended into the deeper soil layers 58 cm (23 in) in the low-gas landfill area. These roots were generally closer to the trunk than were the shallower roots. None of the roots growing in the high-gas landfill (Figure 17) area extended below the 18-cm (7-in) depth. The arrow in Figure 17 indicates one root which started to grow down toward the refuse but died when it reached the 18-cm (7-in) depth. The soil at this depth was very dark in color and had a septic odor. A hole was dug at this location in order to measure the cover soil depth. Only 10-cm (4-in) of soil was found between the dead root tip and the refuse layer. Apparently, no more than 28-cm (11-in) of cover soil had been placed at this location. There was an abundance of shallow roots growing from this tree (Figure 17). Shallow roots appeared infrequently on the two poplar trees on the control plot (Figure 18 and 19), whereas, deeper roots were prevalent (black arrows in Figures 18 and 19 A and B).

The photograph in Figure 20 is of the exposed root system of the poplar tree growing in the high-gas landfill area. The large root toward the bottom of the photograph with the black dot in the center was the deepest living root on this tree. It penetrated the soil to the 15-cm (6-in) depth and then grew upward to the soil surface where it branched, producing many shallow roots. The majority of the other roots in this photograph also grew toward the soil surface. These roots grew from approximately the 10-cm (4-in) soil depth to the top 2.5 cm (1 in) of the soil surface.

2 OF 3

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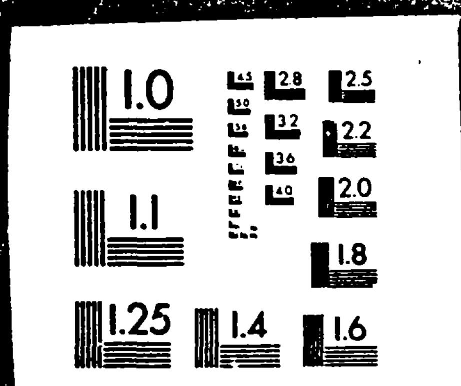

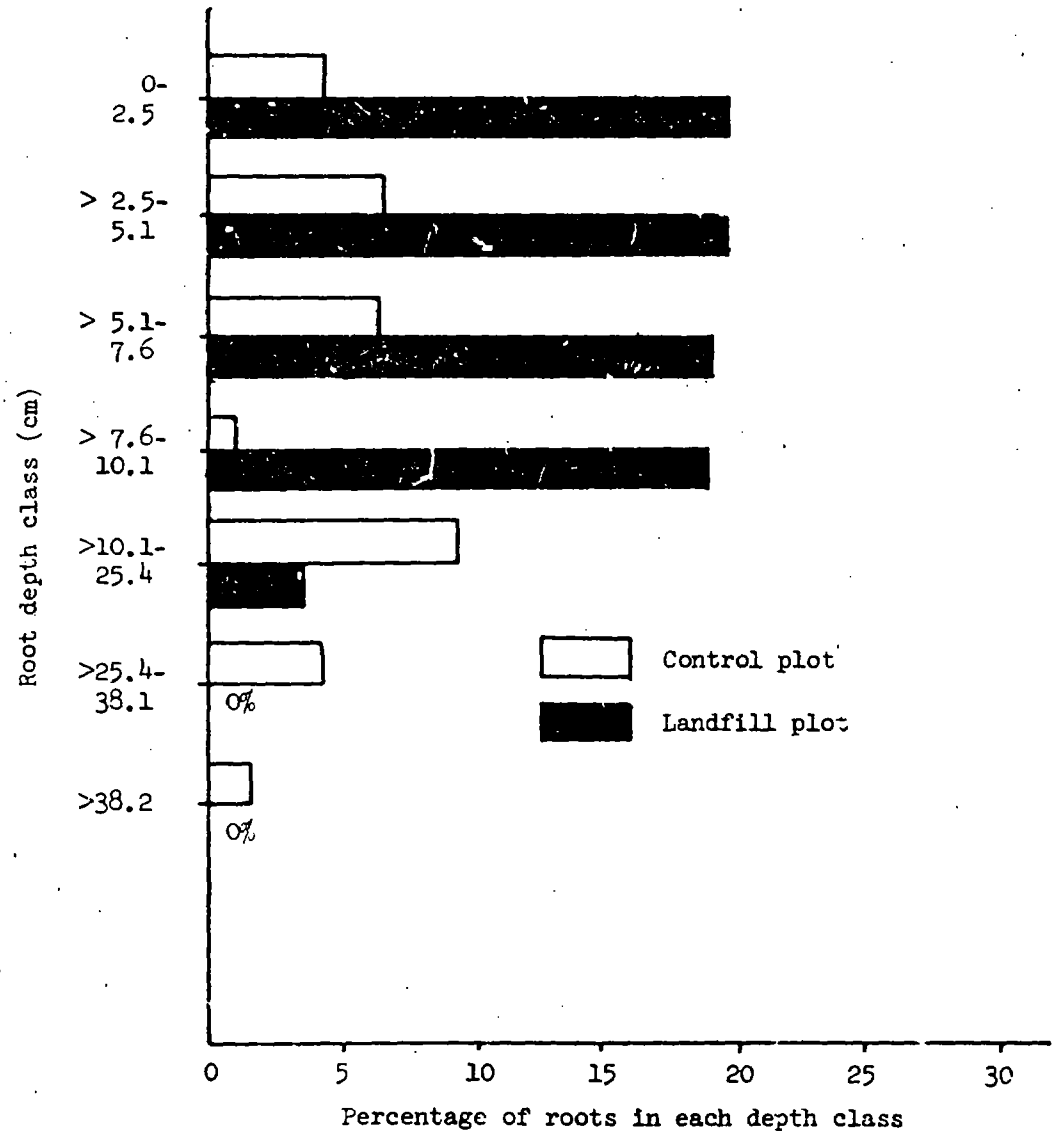

Figure 15. Vertical root distribution of small green ash in landfill and control plots. Each value is the mean for two trees.

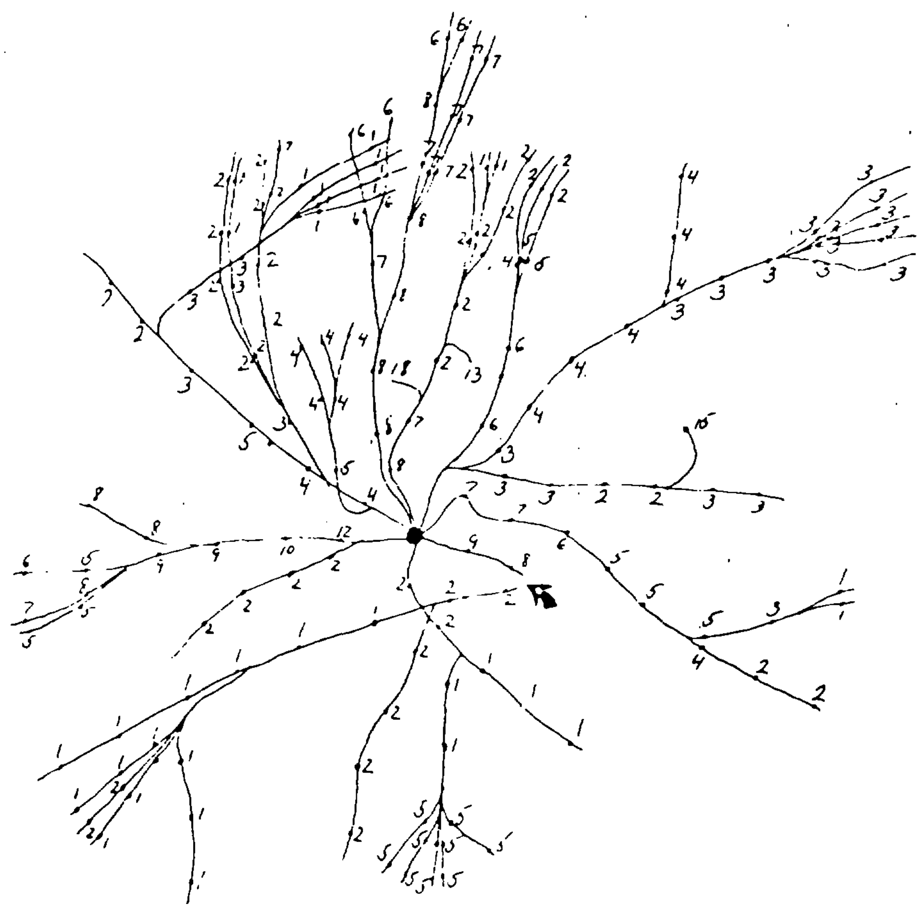

Figure 41. Diagram of hybrid poplar sapling A root system on the landfill low-gas plot indicating root depth at 30.5-cm (12-in) intervals.

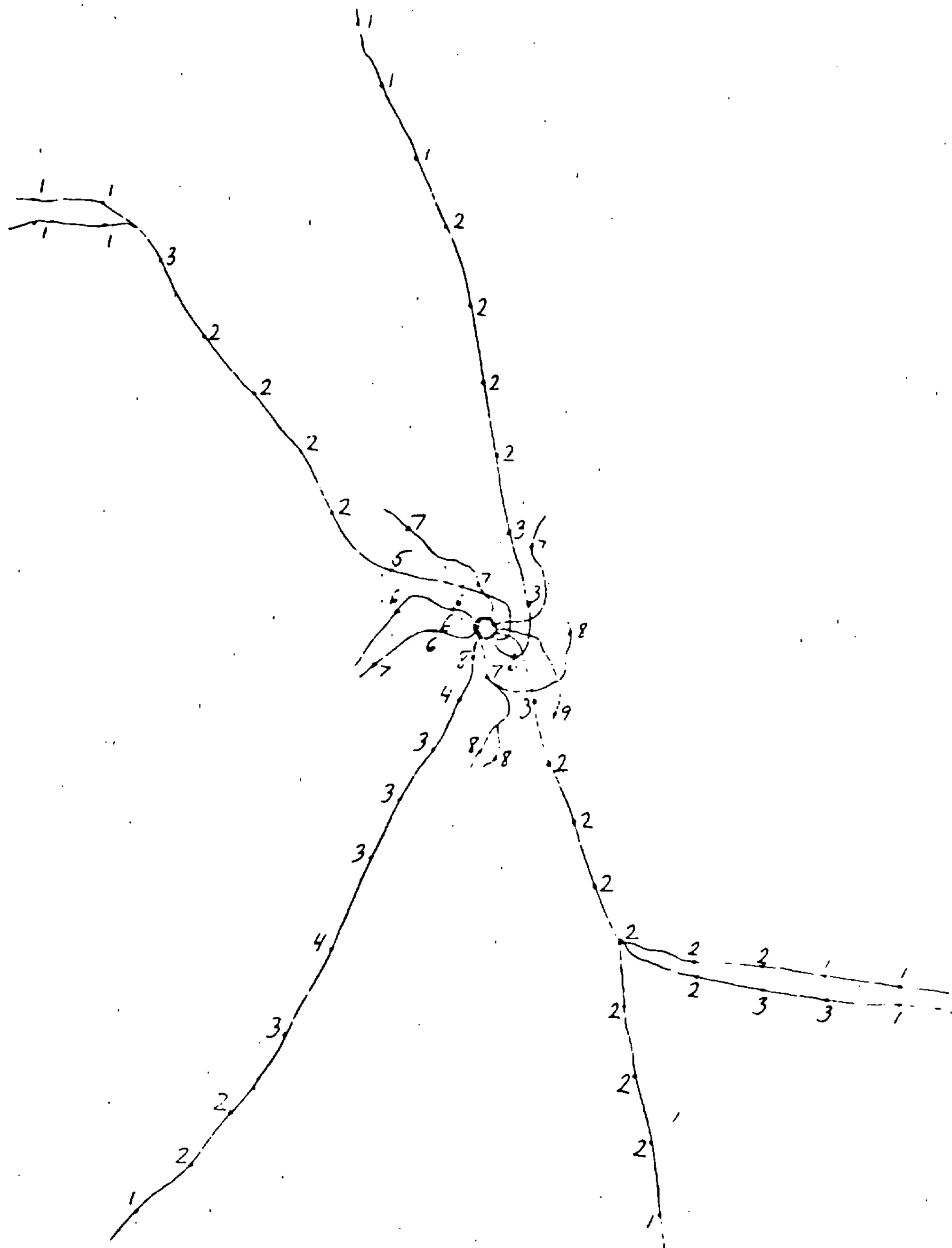

Figure 40. Diagram of hybrid poplar sapling B root system on the high-gas landfill plot indicating root depth at 30.5-cm (12-in) intervals.

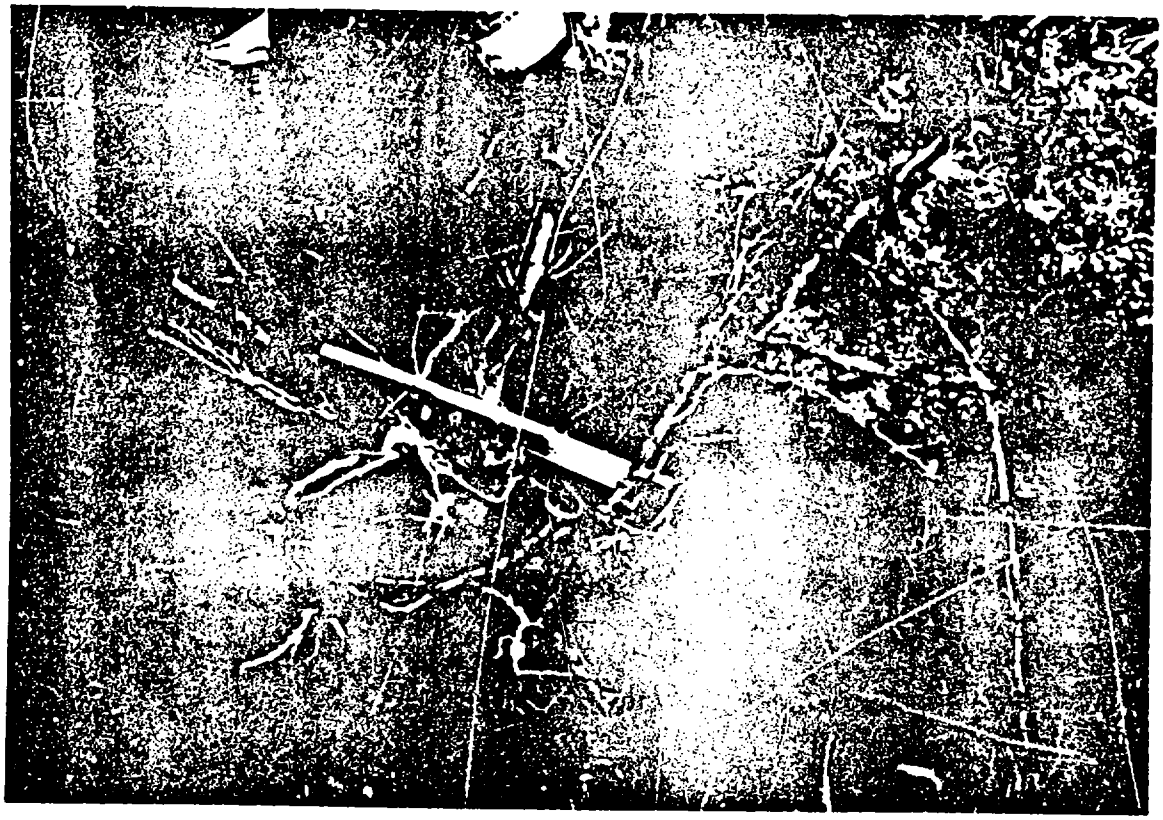

Figure 39. Root system of hybrid poplar sapling on landfill plot.

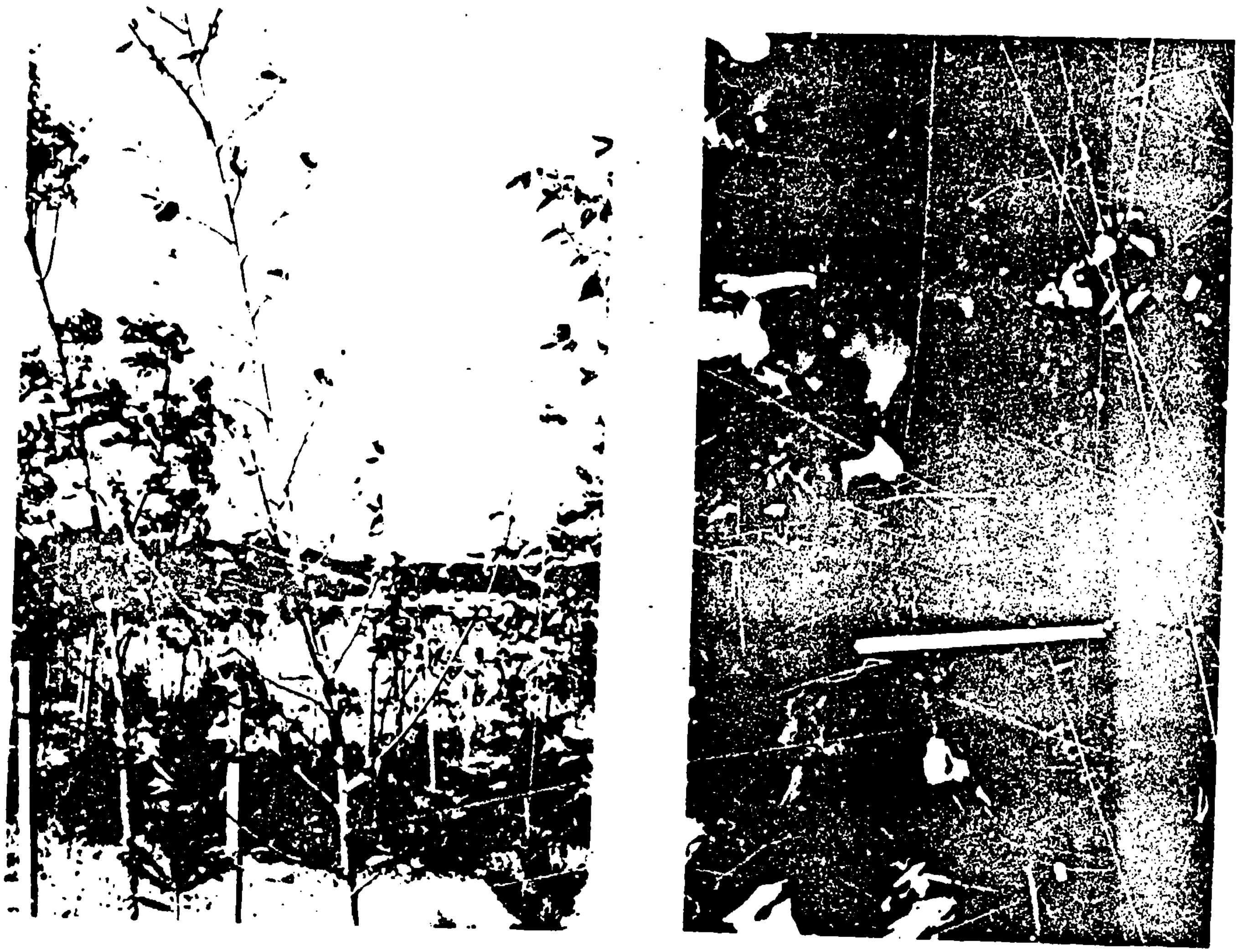

Figure 38. Hybrid poplar trees on landfill (A) and control (B) plots.

The roots of two hybrid poplar saplings were excavated on the landfill plot; one (tree B) was in a high-gas area where the CO_2 concentration at the 20-cm (8-in) soil depth during the years 1977, 1978 and 1979 averaged 7.9%; CH_4 averaged 1.8%; and O_2 averaged 17.1%. The other landfill tree (A) was in a low-gas area (CO_2=1.2%, CH_4=0.0%; O_2=19.1%) (Table 50). Two poplar saplings were also excavated on the control plot (Table 50). The concentrations of CO_2, CH_4 and O_2 on the control were 1.2%, 0.0% and 19.1%, respectively. The poplar in the high-gas area, which died by September 1979, (Figure 38A), had made poor growth compared to the control poplars (Figure 38B) during each of the four years it remained alive. Many poplar roots at the base of this landfill tree (B) had died before root excavation operations began. The four roots which remained alive (arrows, Figure 39) originated from the stump at the 15-cm (6-in) depth or greater and grew toward the soil surface. The ends of each of these four roots were located in the top 2.5-cm (1-in) of soil (Figure 40). Most of the remaining roots in Figure 39 were dead at the time of excavation.

Most poplar roots in the low-gas area also grew toward the soil surface (Figure 41). An example of one root growing straight up toward the soil surface is indicated by the arrows in Figures 41 and 42. This root originated (arrow at top of picture) from the root stock at the 30-cm (12-in) depth and grew straight upward (arrow at middle of upward riser) to the two in (5 cm) soil depth.

Roots of excavated control poplar trees did not tend to grow toward the soil surface as did roots on the landfill areas as evidenced by the root depth values in Figures 43 and 44. Deep roots which were scarce in the landfill area were not uncommon in the control plot. The roots of a control poplar (Tree A) at the base of the rule in Figure 45 are approximately 25 cm (10 in) deep. Mean root depth for both the landfill trees was less than that in the control area (Table 50). Total root length for poplar in the high-gas landfill area was less than half of that in the low-gas area and poplars in both landfill areas produced less total root length than both poplars in the control area.

Carbon dioxide concentrations in the vicinity of two honey locust trees which were later excavated, averaged 5.5% at the 20-cm (8-in) depth during 1977, 1978 and 1979; CH_4 and O_2 in the soil substrate of honey locust in the control plot were 1.1%, 0.0%, and 18.9%, respectively.

The majority of roots on both landfill trees were found in the top 5-cm (2-in) of soil (Table 51, Figures 46 and 47). Many roots reached toward the soil surface as they grew away from the trunk. The arrows in Figure 47 and 48 point to a 3.6 m long root extending away from the trunk shown in the foreground. This root originated at the 5-cm (2-in) depth on the root stock and grew at this level throughout it's entire length.

The root systems of the two excavated control honey locust trees (Table 51) were approximately twice as deep and more than twice as long as the trees on the landfill. The roots of control trees were fairly evenly distributed throughout the soil depths; however, locust roots on the landfill were concentrated near the surface. Roots on the control trees did not rise

TABLE 49. NUMBER OF 30.5-cm (12-IN) LARGE GREEN ASH (SAPLINGS) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO_2, CH_4, O_2 CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

		Landfill				Control			
		Tree A (low gas)		Tree B (high gas)		Tree A		Tree B	
Soil depth in	cm	# of root sections	%	# of root sections	%	# of root sections	%	# of root sections	%
1	2.5	29	15.3a+	49	46.7b	38	12a	36	11.9a
2	5.1	50	26.1	34	32.2	49	15.5	38	12.6
3	7.6	14	7.4	10	9.5	30	9.5	45	14.9
4	10.1	15	7.9	0	0	37	11.7	27	8.9
5	12.7	10	5.3	2	1.9	19	6.0	26	8.6
6	15.2	14	7.4	1	1.0	25	7.9	17	5.6
7	17.8	10	5.3	0	0	19	6.0	11	3.6
8	20.3	19	10.0	0	0	9	2.8	10	3.3
9	22.8	6	3.2	0	0	10	3.2	22	7.3
10	25.4	12	6.3	1	1.0	26	8.2	11	3.6
11	27.9	6	3.2	0	0	7	2.2	28	9.3
12	30.5	5	2.6	0	0	28	8.8	18	6.0
13	33.0	0	0	1	1.0	4	1.3	7	2.3
14	35.6	0	0	4	3.8	13	4.1	6	2.0
15	38.1	0	0	3	2.9	1	0.3	0	0
16	40.6	0	0	0	0	2	0.6	0	0
Total length (m)		57.9		32.0		96.6		92.0	
Mean depth (cm)		11.9		6.6		14.7		14.7	
Maximum depth (cm)		30.5		38.1		40.6		35.6	
CO_2		3.9		13.1		1.2		1.1	
O_2		18.3		12.3		19.8		19.6	
CH_4		1.3		7.3		0.0		0.0	

\+ Columns with similar letters have a similar root distribution by Chi-Square analysis at $P<.01$.

Figure 37. Root system of green ash sapling A on control plot.

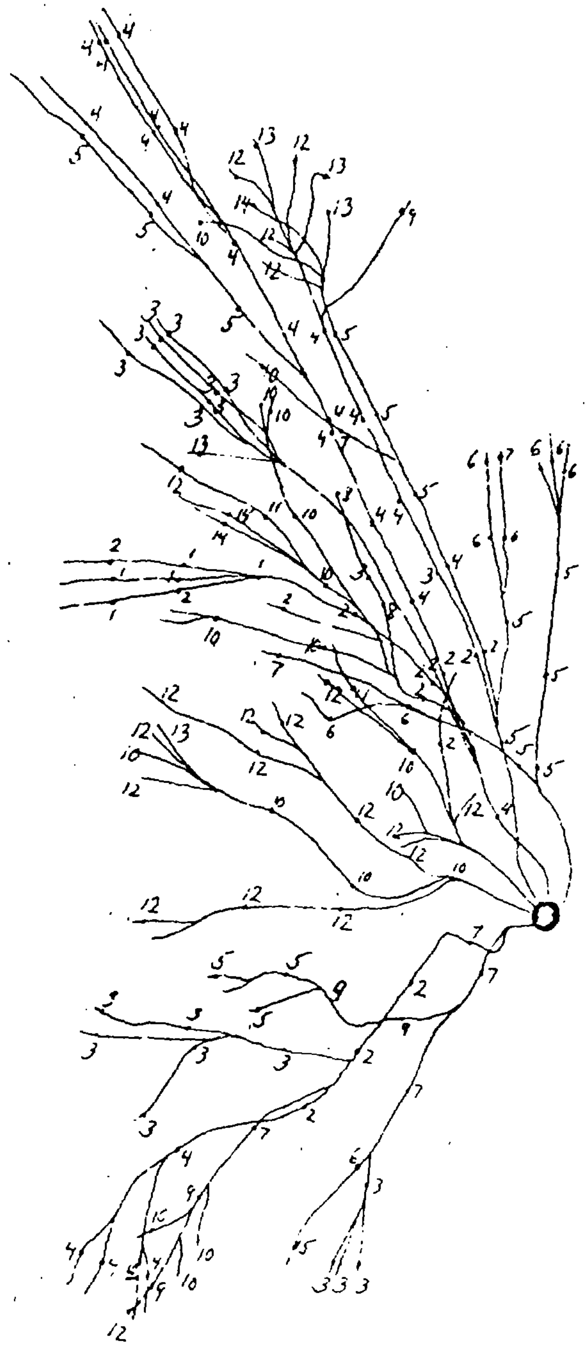

Figure 36. (continued)

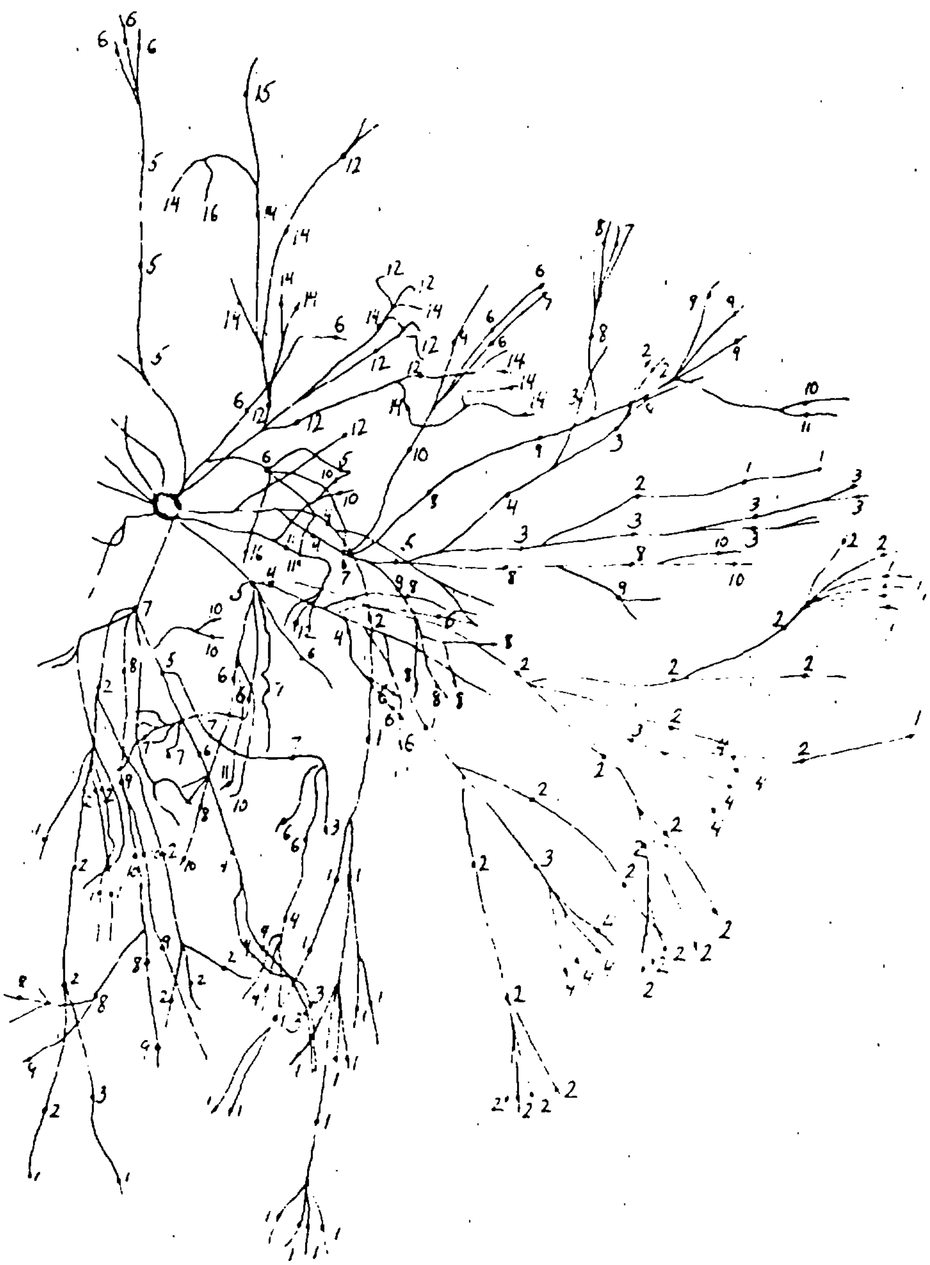

Figure 36. Diagram of green ash sapling A root system on the control plot indicating root depth at 30.5-cm (12-in) intervals. (continued)

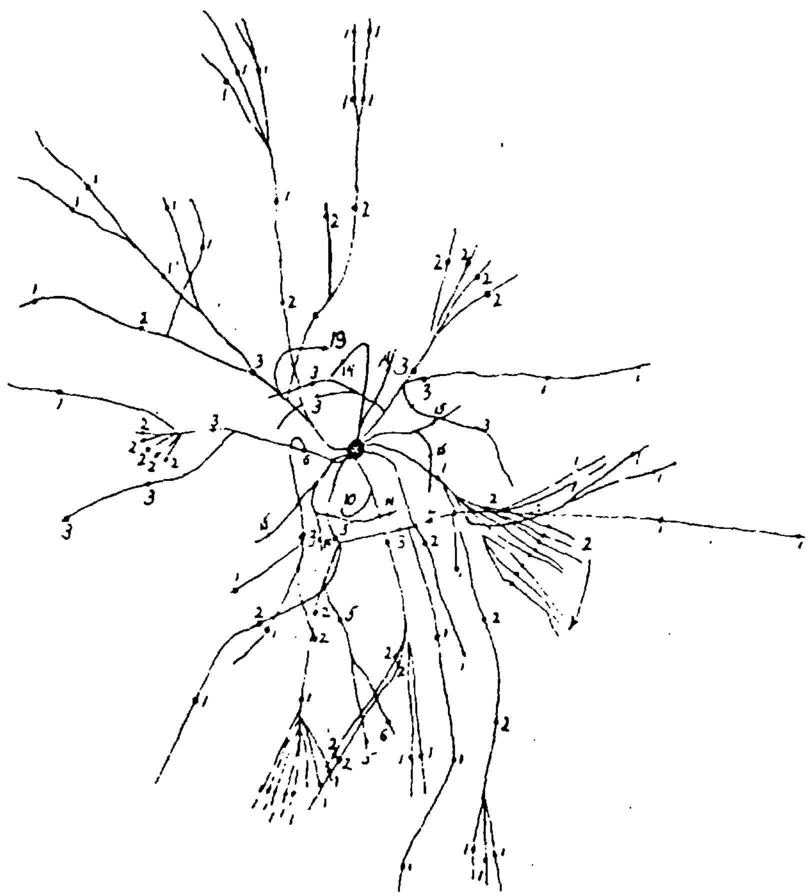

Figure 35. Diagram of green ash sapling B root system on high-gas landfill plot indicating root depth at 30.5-cm (12-in) intervals.

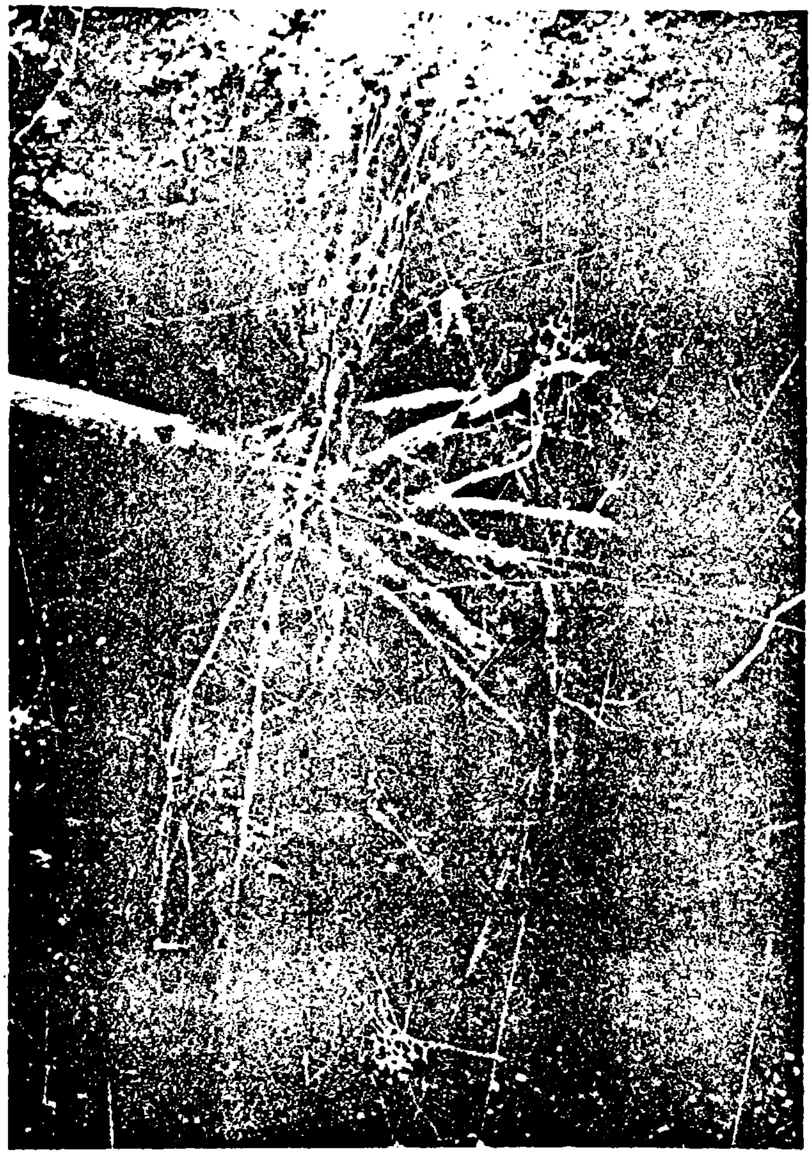

Figure 34. Root system of green ash sapling B on high-gas landfill plot.

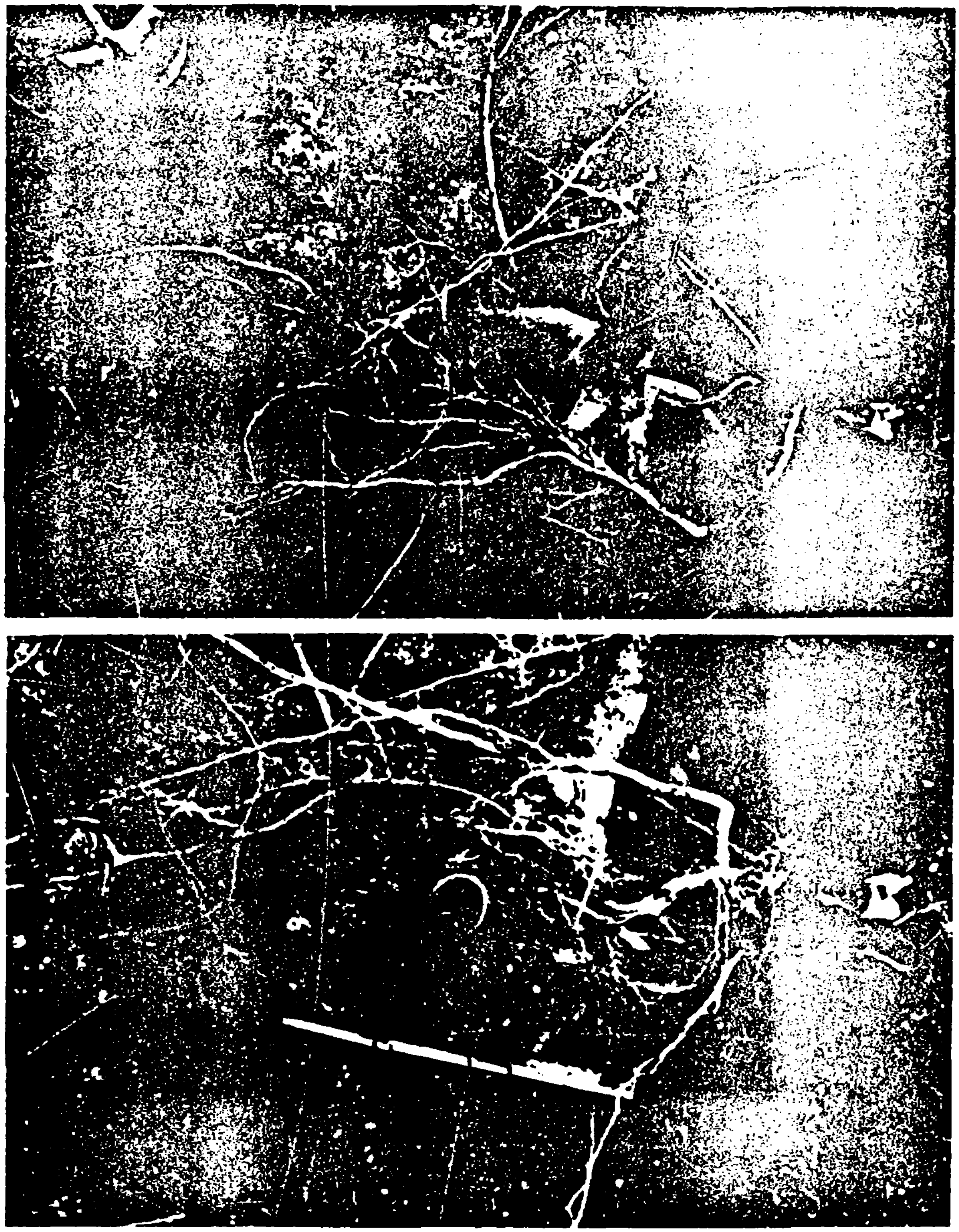

Figure 33. Root system of green ash sapling B on low-gas landfill plot.

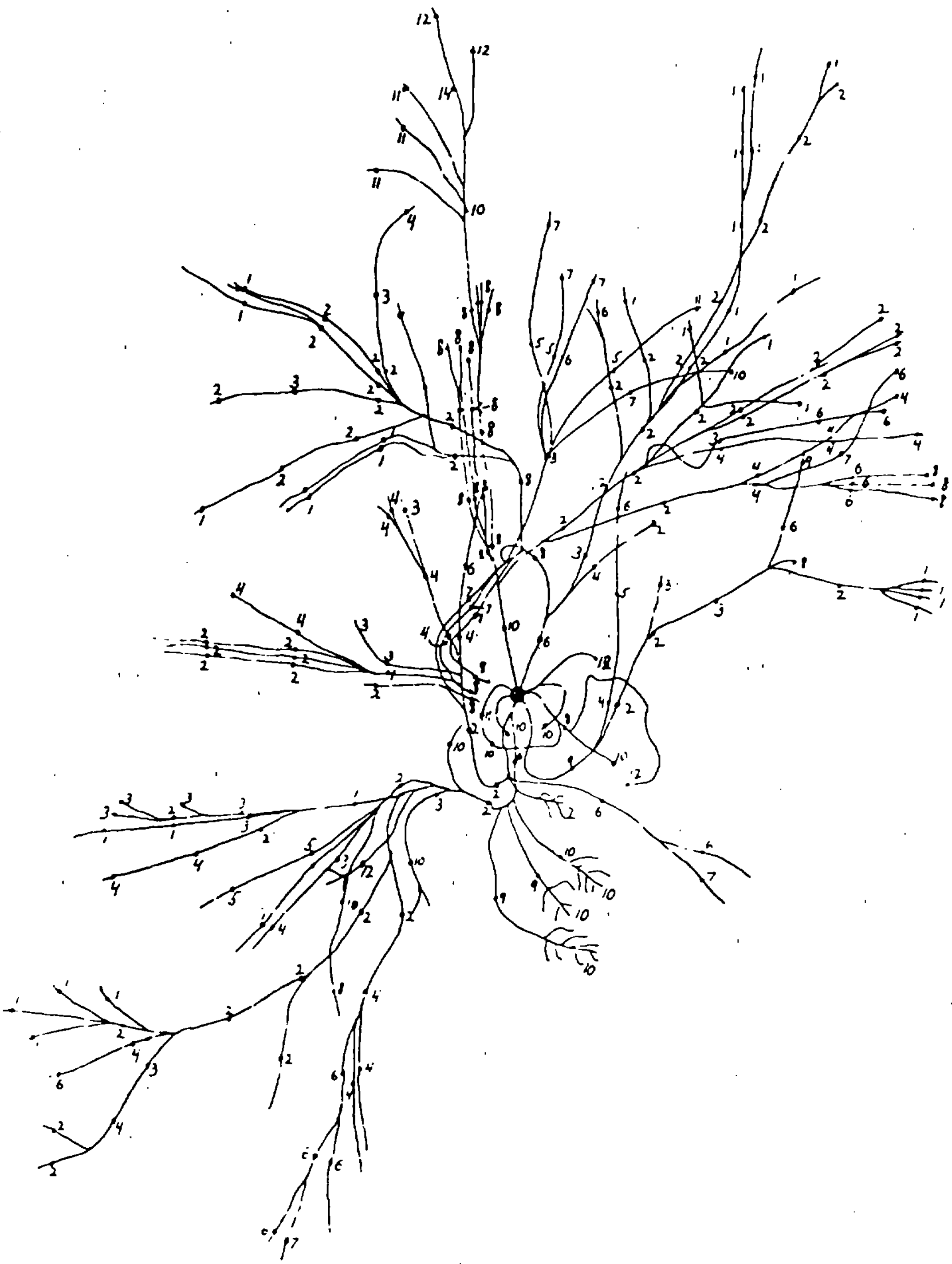

Figure 32. Diagram of large green ash sapling A root system on landfill indicating root depth at 30.5-cm (12-in) intervals.

Figure 31. Root system of green ash seedling A on the control plot.

on the control plot. Ash seedlings on the control area did not form the matted short-root zone found on the landfill trees. Several control tree roots, like the one shown in Figure 31 (arrow), grew almost straight down. This was not found on the landfill trees.

TABLE 48. MEAN ROOT DEPTH AND TOTAL ROOT LENGTH FOR SMALL GREEN ASH IN HIGH GAS AND LOW GAS AREAS ON LANDFILL PLOT AND IN TWO AREAS ON CONTROL PLOT

Location	Mean Root depth (cm)	Total Root length (m)
Landfill*		
Low gas area A	9.6	9.1
High gas area B	7.5	7.0
Control+		
Area A	22.6	21.3
Area B	19.8	15.8

* Carbon dioxide in the high-gas area averaged 14.7% at the 20 cm (8 in) depth and in the low gas area 5.2% at the 20 cm (8 in) depth from 1978 through 1979.

\+ Carbon dioxide averaged 1.1% at the 20 cm (8 in) depth from 1978 through 1979.

The root systems of four large green ash saplings, two on the landfill and two on the control plot were excavated. The number of roots at each soil depth is given in Table 49. Tree A (diagrammed in Figure 32) growing in a low-gas area where the CO_2 concentrations during 1977, 1978 and 1979 averaged 3.9%, CH_4 averaged 1.3% and O_2 averaged 18.3% produced a mat of short roots at the 25-cm (10-in) depth illustrated in Figures 33A and B. Immediately below the root mat was a dark soil layer which had the odor of decomposing refuse (arrows, Figure 33B). A less-dense mat-like formation was found on ash sapling B (Figure 34) in the high-gas landfill area (CO_2=13.1%, CH_4=7.3%, O_2=12.3%); however, a large portion of the roots (46.7%) was found in the top 2.5 cm (1 in) of soil (arrows, Figure 34 and Figure 35). The large diameter roots in the center of Figure 34 were present when the tree was planted in 1976, so they were not included in any data analysis.

Control ash root systems were very well developed (Figures 36A and B and 37). The roots of control ash were more evenly distributed depthwise in the soil than those of tree A and tree B in the low-and high-gas landfill areas (Table 49). Mean root depth (6.6 cm) (Table 49) was shallower and total root length (32.0 m) lower in tree B in the high-gas area than in tree A in the low-gas landfill area and both were reduced compared to the control (Table 49).

Figure 30. Close-up photographs of root systems of green ash seedlings on landfill high gas (A) and landfill low-gas (B) plots.

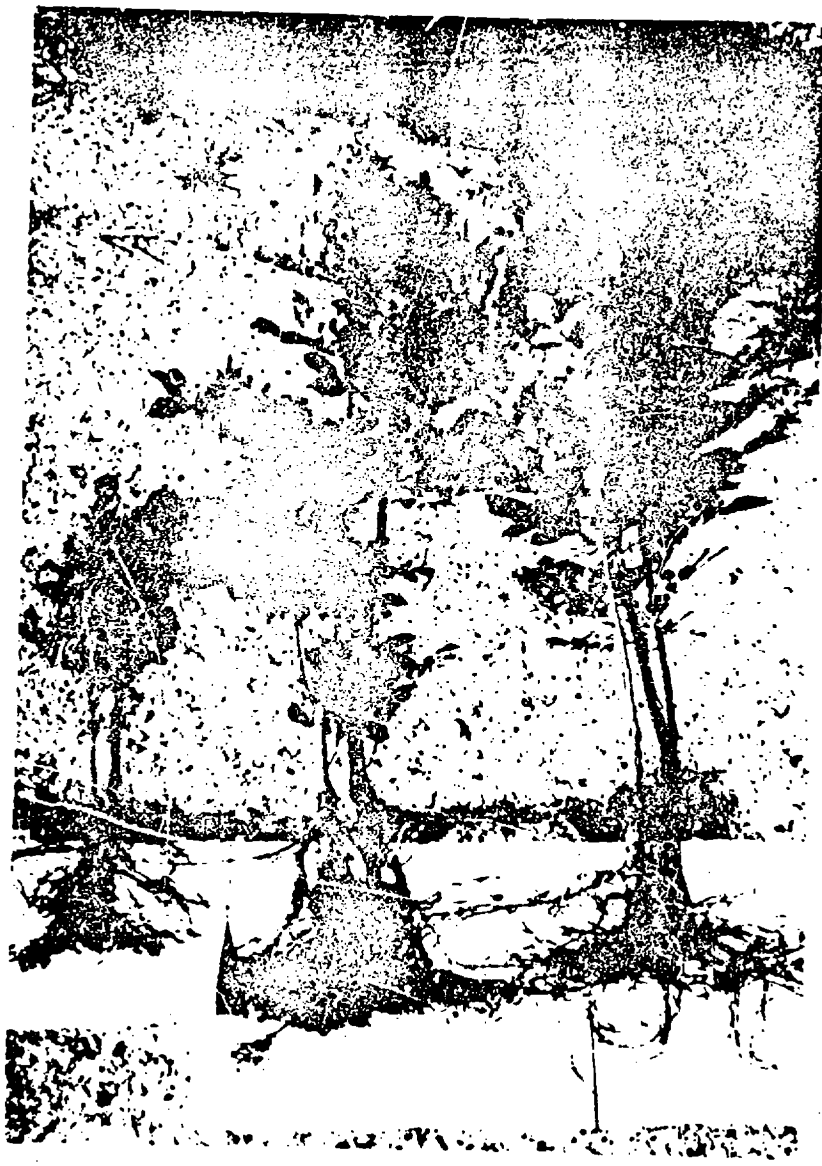

Figure 29. Root systems of green ash seedlings on control (A), low-gas (B), and high-gas (C) landfill plots.

TABLE 47. NUMBER OF 30.5-cm (12-IN) GREEN ASH (SMALL TREES) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO_2, CH_4 AND O_2 CONCENTRATION ON LANDFILL AND CONTROL PLOTS

		Landfill				Control			
		Tree A (low gas)		Tree B (high gas)		Tree A		Tree B	
Soil depth in	cm	# of root sections	%	# of root sections	%	# of root sections	%	# of root sections	%
1	2.5	5	16.7b+	5	20.0c	6	8.8a	0	0a
2	5.1	3	10.0	7	28.0	1	1.4	6	11.5
3	7.6	5	16.7	5	20.0	5	7.1	3	5.8
4	10.1	6	20.0	4	16.0	1	1.4	1	1.9
5	12.7	5	16.7	1	4.0	5	7.1	0	0
6	15.2	4	20.0	1	4.0	4	5.7	3	5.8
7	17.8	1	16.7	2	8.0	5	7.1	7	13.6
8	20.3	1	13.1	0	0	3	4.3	9	17.3
9	22.8	0	3.4	0	0	0	0	12	23.0
10	25.4	0	3.4	0	0	10	14.4	3	5.8
11	27.9	0	0	0	0	8	11.4	1	1.9
12	30.5	0	0	0	0	8	11.4	5	9.6
13	33.0	0	0	0	0	4	5.7	0	0
14	35.6	0	0	0	0	4	5.7	0	0
15	38.1	0	0	0	0	3	4.3	0	0
16	40.6	0	0	0	0	2	2.8	1	1.9
17	43.2	0	0	0	0	1	1.4	1	1.9
Total length (m)		9.1		7.6		21.3		15.8	
Mean depth (cm)		9.6		7.6		22.6		19.8	
Maximum depth (cm)		20.3		17.8		43.2		43.2	
CO_2		5.2		14.7		1.1		1.1	
CH_4		1.9		16.1		0.0		0.0	
O_2		17.8		6.1		19.8		19.8	

+ Columns with different letters have statistically different distribution by Chi-Square Analysis at P<.01.

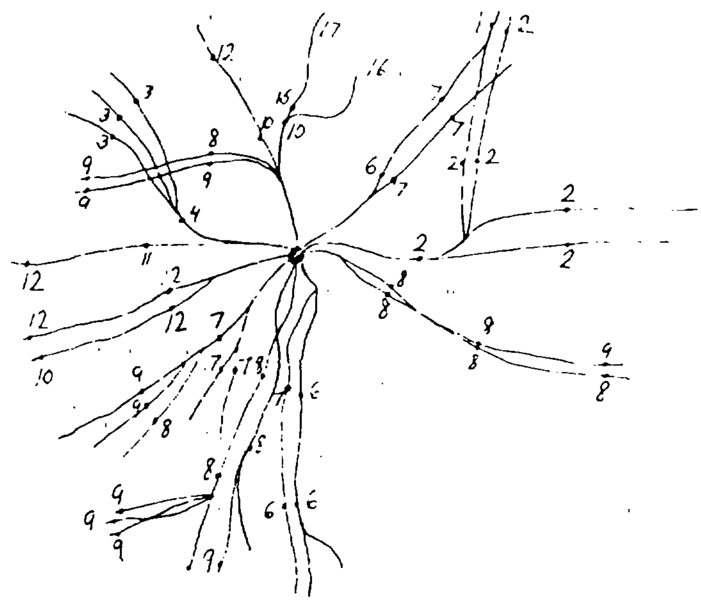

Figure 28. Diagram of green ash seedling B root system on control plot indicating root depth at 30.5-cm (12-in) intervals.

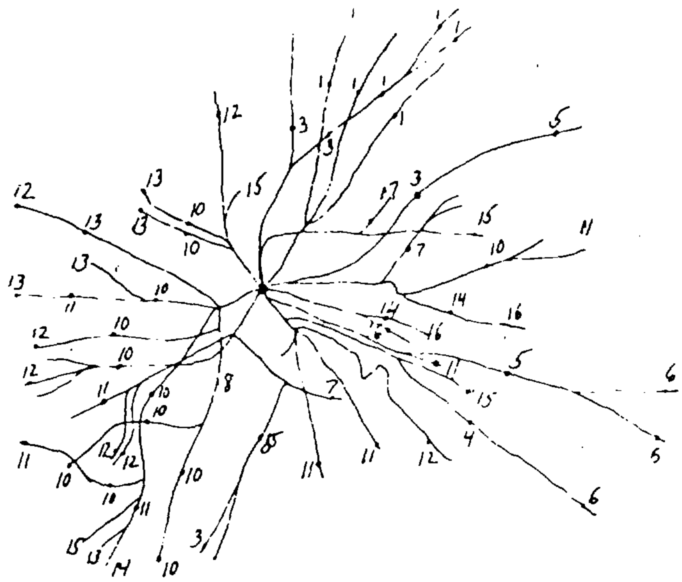

Figure 27. Diagram of green ash seedling A root system in control plot indicating root depth in inches at 30.5-cm (12-in) intervals.

Figure 42. Root system of hybrid poplar sapling A on landfill low-gas plot.

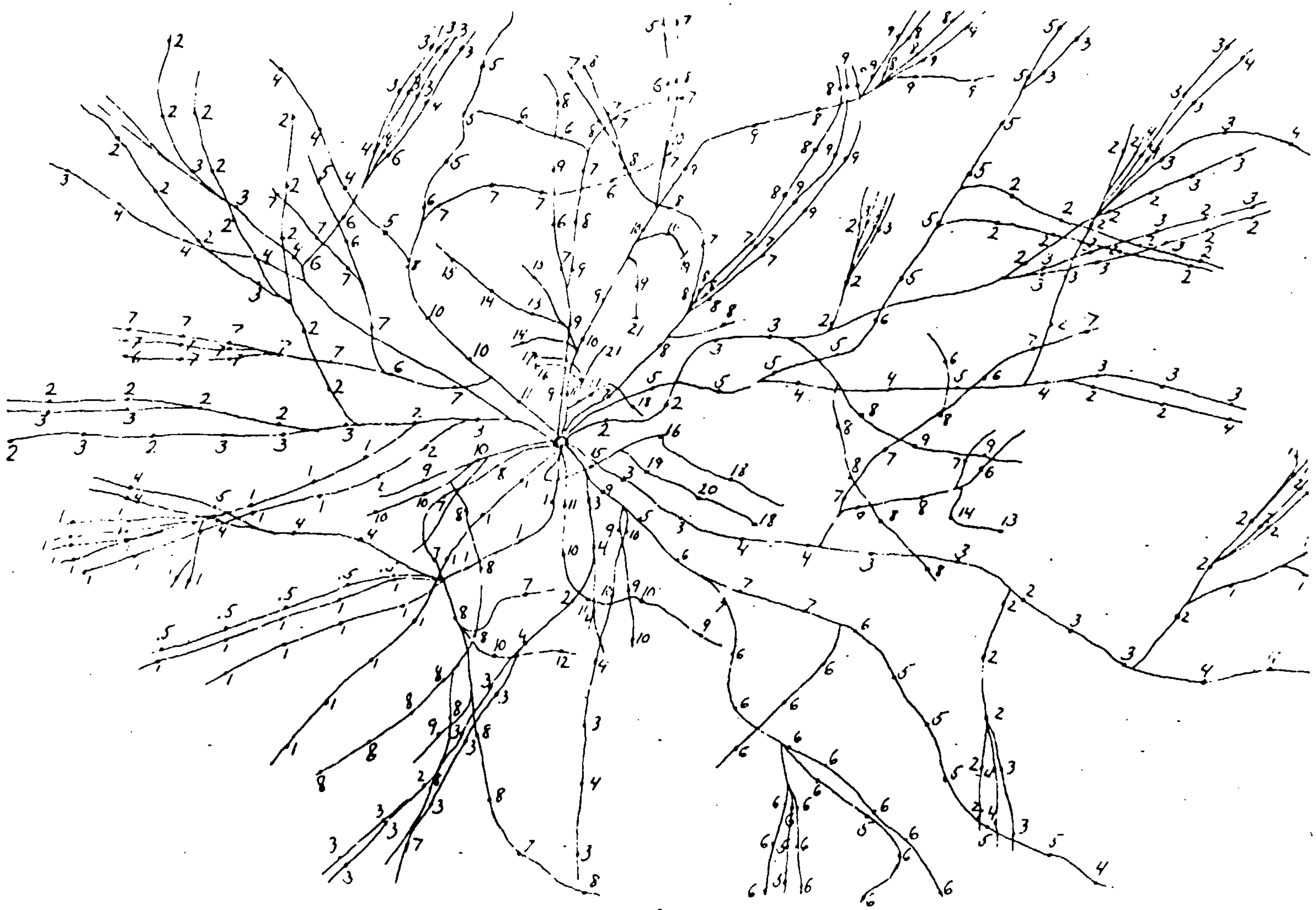

Figure 43. Diagram of hybrid poplar sapling A roots system on control plot indicating root depth at 30.5-cm (12-in) intervals.

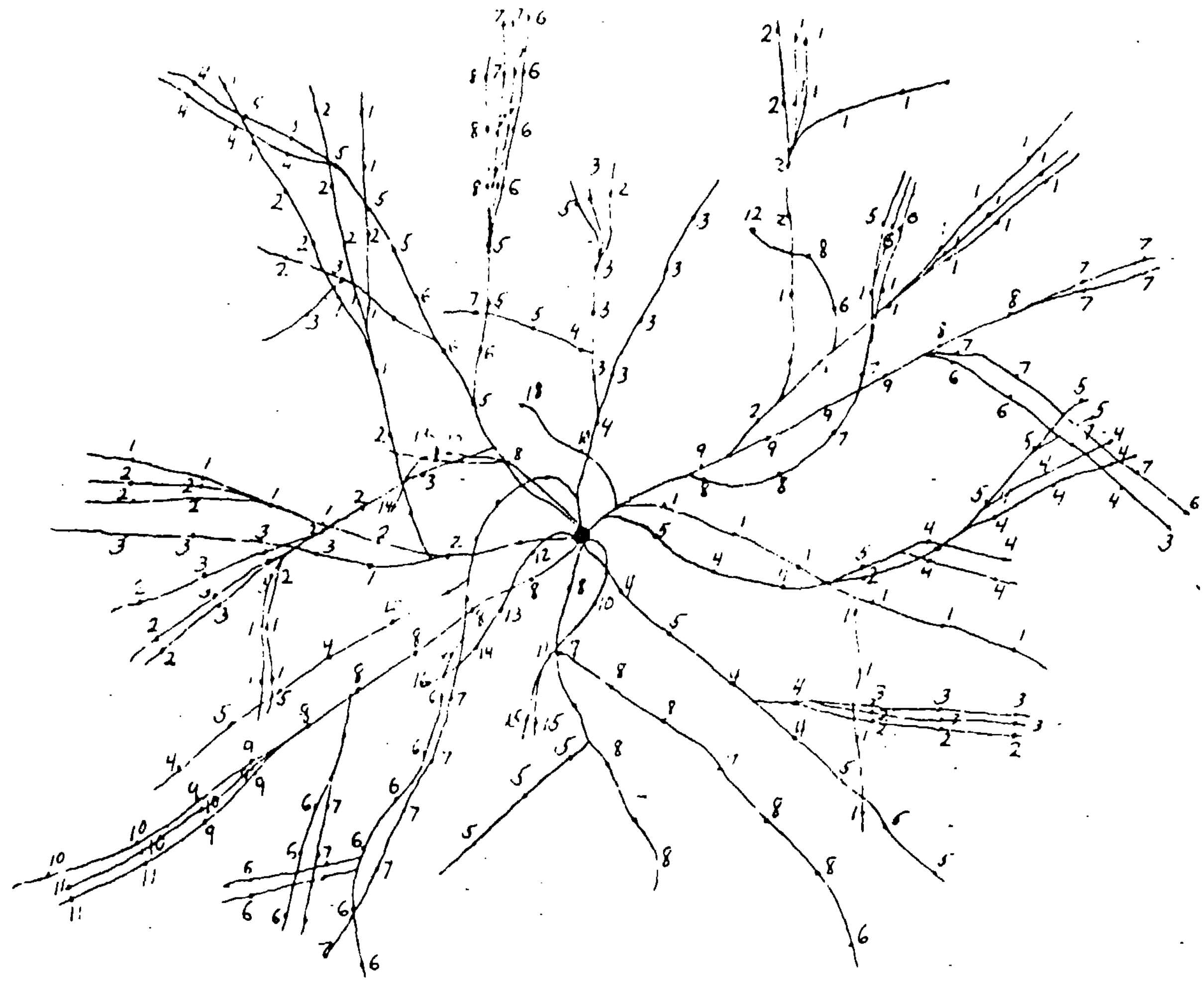

Figure 44. Diagram of hybrid poplar sapling B root system on control plot indicating root depth at 30.5-cm (12-in) intervals.

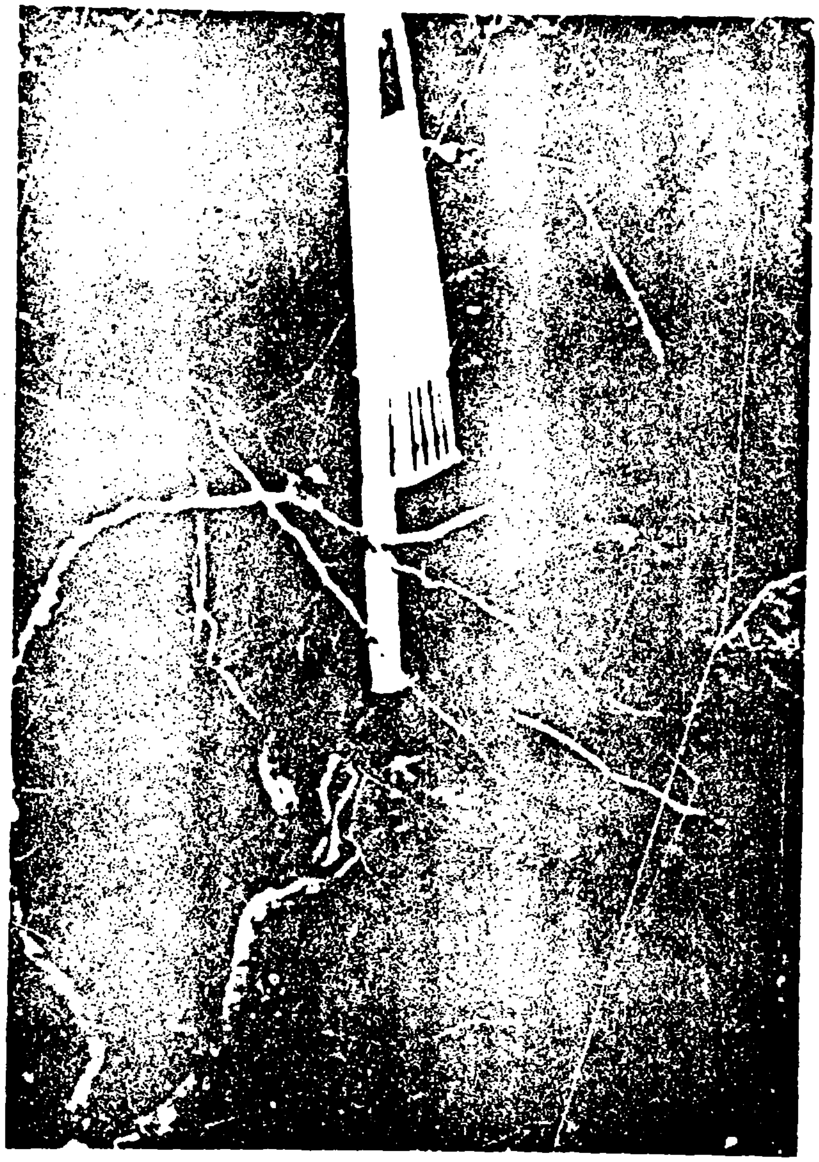

Figure 45. Root system of hybrid poplar sapling A on control plot.

TABLE 50. NUMBER OF 30.5-cm (12-IN) HYBRID POPLAR (SAPLINGS) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH, TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO_2, CH_4 AND O_2 CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

		Landfill				Control			
		Tree A (low gas)		Tree B (high gas)		Tree A		Tree B	
Soil depth in	cm	# of root sections	%	# of root sections	%	# of root sections	%	# of root sections	%
0.5	1.3	11	6.4b+	0	0c	5	1.3a	0	0a
1	2.5	40	23.1	13	20.6	42	10.6	44	18.2
2	5.1	39	22.5	20	31.7	68	17.1	30	12.3
3	7.6	24	13.9	10	15.9	55	13.8	27	11.1
4	10.1	12	6.9	2	3.2	27	6.8	23	9.5
5	12.7	10	5.8	1	1.6	27	6.8	26	10.7
6	15.2	9	5.2	5	7.9	32	8.1	27	11.1
7	27.9	13	7.5	7	11.1	32	8.1	25	10.3
8	20.3	9	5.2	4	6.4	44	11.1	18	7.4
9	22.8	2	1.1	1	1.6	30	7.6	5	2.1
10	25.4	1	0.6	0	0	14	3.7	6	2.5
11	27.9	0	0	0	0	6	1.5	3	1.2
12	30.5	0	0	0	0	0	0	1	0.4
13	33.0	1	0.6	0	0	0	0.2	2	0.8
14	35.6	0	0	0	0	3	0.7	2	0.8
15	38.1	1	0.6	0	0	3	0.7	2	0.8
16	40.6	0	0	0	0	1	0.2	1	0.4
17	43.2	0	0	0	0	0	0	0	0
18	45.7	1	0.6	0	0	2	0.5	1	0.4
19	48.3	0	0	0	0	2	0.5	0	0
20	50.8	0	0	0	0	1	0.2	0	0
21	53.3	0	0	0	0	2	0.5	0	0
Total length (m)		52.7		19.2		121.0		74.0	
Mean depth (cm)		8.4		8.6		12.5		13.2	
Maximum depth (cm)		45.7		22.8		53.3		45.7	
CO_2		1.2		7.9		1.2		1.2	
O_2		19.1		17.1		19.1		19.1	
CH_4		0.0		1.8		0.0		0.0	

+ Columns with similar letters have similar root distributions at P<.01 by Chi-Square Analysis.

TABLE 51. NUMBER OF 30.5-cm (12-IN) HONEY LOCUST ROOT SECTIONS AND PERCENTAGE TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO_2, CH_4 AND O_2 CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

		Landfill				Control			
		Tree A		Tree B		Tree A		Tree B	
Soil depth in	cm	# of roots	%	# of roots	%	# of roots	%	# of roots	%
1	2.5	3	6.7a+	2	3.0a	0	0b	0	0b
2	5.1	24	53.3	40	60.6	29	16.3	33	19.4
3	7.6	4	8.9	11	16.7	16	9.1	9	5.3
4	10.1	6	13.4	5	7.6	7	3.9	9	5.3
5	12.7	3	6.7	0	0	6	3.4	33	19.4
6	15.2	1	2.2	0	0	11	6.2	17	10.0
7	17.8	0	0	5	7.6	18	10.1	9	5.3
8	20.3	2	4.4	1	1.5	38	21.3	17	10.0
9	22.8	1	2.2	1	1.5	8	4.5	14	8.2
10	25.4	1	2.2	0	0	16	9.1	12	7.1
11	27.9	0	0	0	0	19	10.7	5	2.9
12	30.5	0	0	1	1.5	9	5.1	6	3.5
13	33.0	0	0	0	0	0	0	3	1.8
14	>33.0	0	0	0	0	1	0.6	2	1.2
Total length (m)		13.7		20.1		54.2		51.8	
Mean depth (cm)		8.9		7.6		17.5		15.7	
Maximum depth (cm)		25.4		20.5		35.6		48.2	
CO_2		5.1		5.9		0.9		1.3	
O_2		16.1		17.5		18.7		19.1	
CH_4		1.6		1.8		0.0		0.0	

+ Columns with similar letters have similar root distributions at P<.01 by Chi-Square Analysis.

Figure 46. Diagram of honey locust tree B root system on landfill plot indicating root depth at 30.5-cm (12-in) intervals.

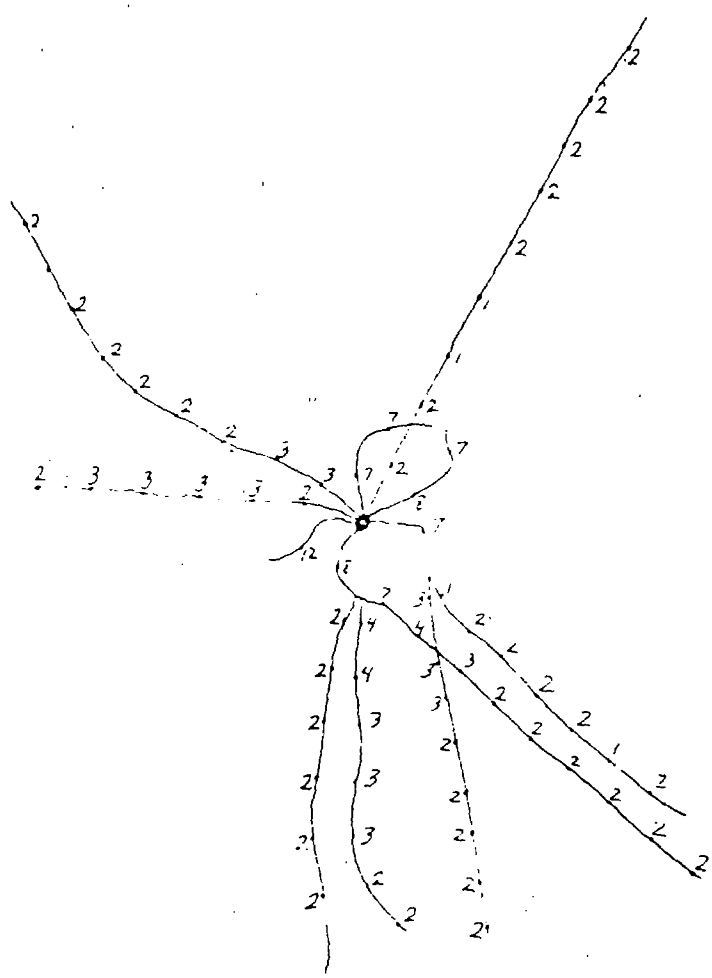

Figure 47. Diagram of honey locust tree A root system on landfill plot indicating root depth at 30.5-cm (12-in) intervals.

Figure 48. Root system of honey locust tree A on landfill plot.

toward the soil surface as they grew away from the trunk (Figures 49 and 50). Several roots such as those indicated with arrows in Figure 51B, grew away from the soil surface. However; control locust roots generally remained at the same soil depth throughout their entire length (Figure 51B) Many roots were found at depths between 10 cm (4 in) and 25 cm (10 in) (Figure 51A). The arrow above the hand shovel shows the approximate location of the soil surface. The root at the tip of the shovel was approximately 25 cm (10 in) deep.

Two Japanese black pine trees were excavated on the landfill and control plots. Carbon dioxide (5.6%) and methane (1.1%) concentrations were higher and oxygen (18.3%) concentrations lower on the landfill than on the control plot (CO_2=1.2%, CH_4=0.0%, O_2=19.8) (Table 52). Root distribution on the landfill plot (Figures 52 and 53) was statistically similar to that in the control plot (Figures 54 and 55). Total root length and mean root depth values on the landfill were similar to those on the control (Table 52). Maximum root depth was slightly greater on the control than on the landfill plot.

Two Norway spruce trees were excavated on the landfill and control plots. Carbon dioxide (4.7%) and methane (0.6%) concentrations were higher and oxygen concentrations were lower (18.4%) on the landfill than on the control (CO_2=1.2%, CH_4=0.0%, O_2=19.8%) (Table 53). Roots of Norway spruce tree A were concentrated very close to the soil surface (Table 53); whereas, roots from tree B were growing in deeper soil layers. The same pattern was observed on the control plot, where one tree A produced a very shallow root system, whereas, the other tree B had many roots in deeper soil layers. Roots on both plots grew very straight and rarely branched (Figures 56, 57, 58, 59). Figure 60 illustrates the shallow root system of the Norway spruce on the landfill plot and Figure 61 demonstrates the shallow roots on the control.

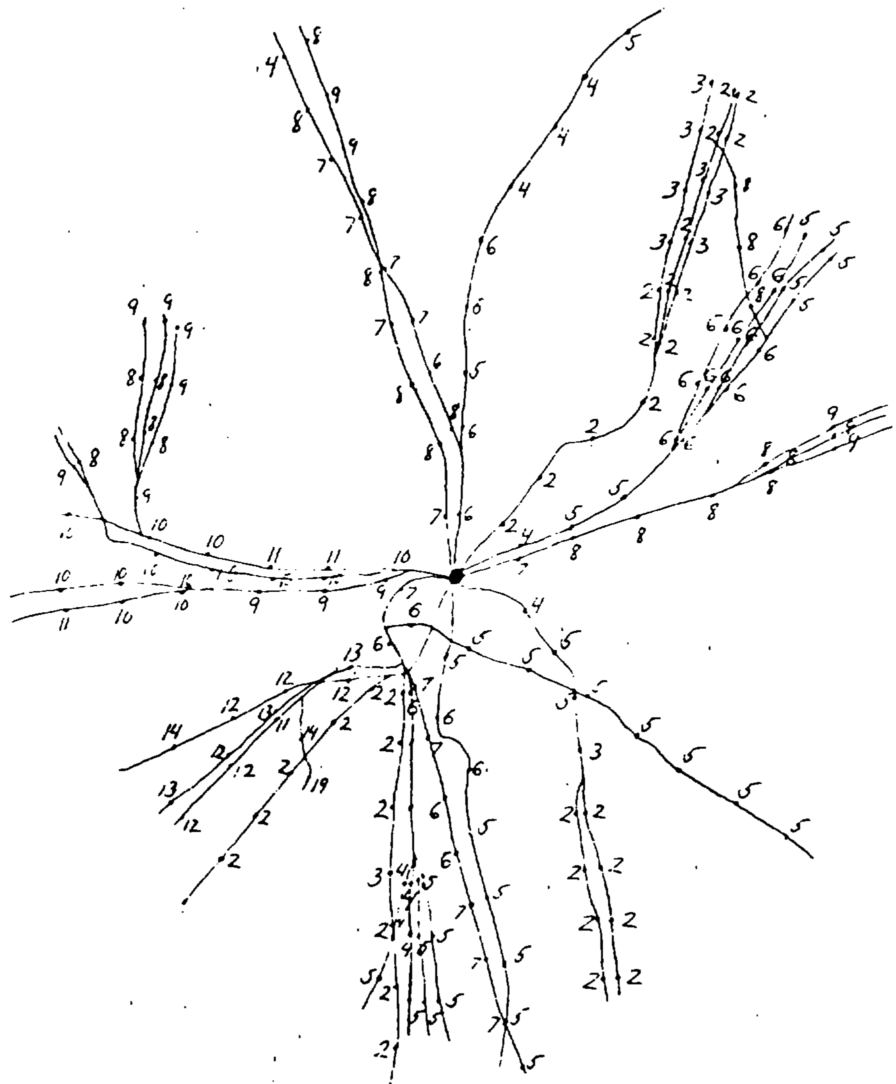

Figure 50. Diagram of honey locust tree B root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

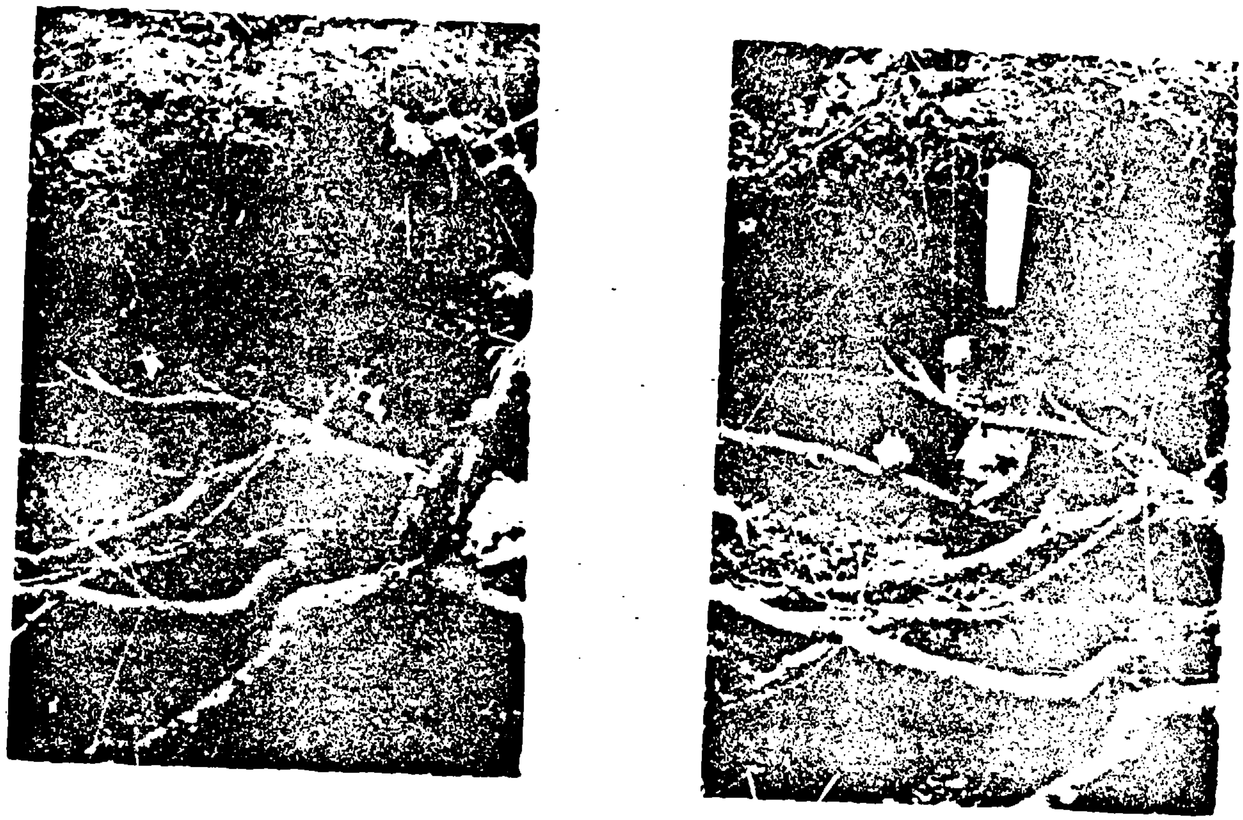

Figure 51. Root system of honey locust tree A on control plot.

TABLE 52. NUMBER OF 30.5-cm (12-IN) JAPANESE BLACK PINE ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH, TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO_2, CH_4 AND O_2 CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

		Landfill				Control			
		Tree A		Tree B		Tree A		Tree B	
Soil depth in	cm	# of roots	%	# of roots	%	# of roots	%	# of roots	%
1	2.5	0	0a+	0	0a	0	0a	2	2.8a
2	5.1	39	56.5	43	46.7	24	30.4	28	38.9
3	7.6	13	18.8	17	18.5	21	26.6	25	34.6
4	10.1	7	10.1	16	17.4	8	10.0	6	8.3
5	12.7	4	5.8	9	9.8	4	5.1	4	5.6
6	15.2	4	5.8	5	5.4	7	8.9	2	2.8
7	17.8	1	1.5	2	2.2	4	5.1	2	2.8
8	20.3	1	1.5	0	0	[illegible]	8.9	1	1.4
9	22.8	0	0	0	0	2	2.5	2	2.8
10	25.4	0	0	0	0	2	2.5	0	0
Total length (m)			21.0		28.0		24.1		21.9
Mean depth (cm)			7.6		8.1		10.4		8.1
Maximum depth (cm)			20.3		17.8		25.4		22.8
CO_2			5.1		6.2		1.2		1.2
O_2			18.9		17.8		19.8		19.8
CH_4			1.4		0.9		0.0		0.0

\+ Columns with similar letters have similar root distributions at $P<.01$ by Chi-Square Analysis.

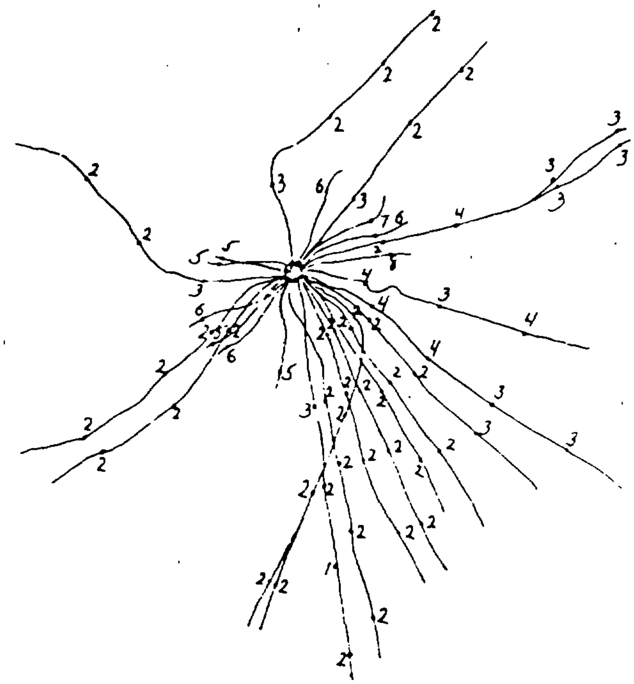

Figure 52. Diagram of Japanese black pine tree A root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

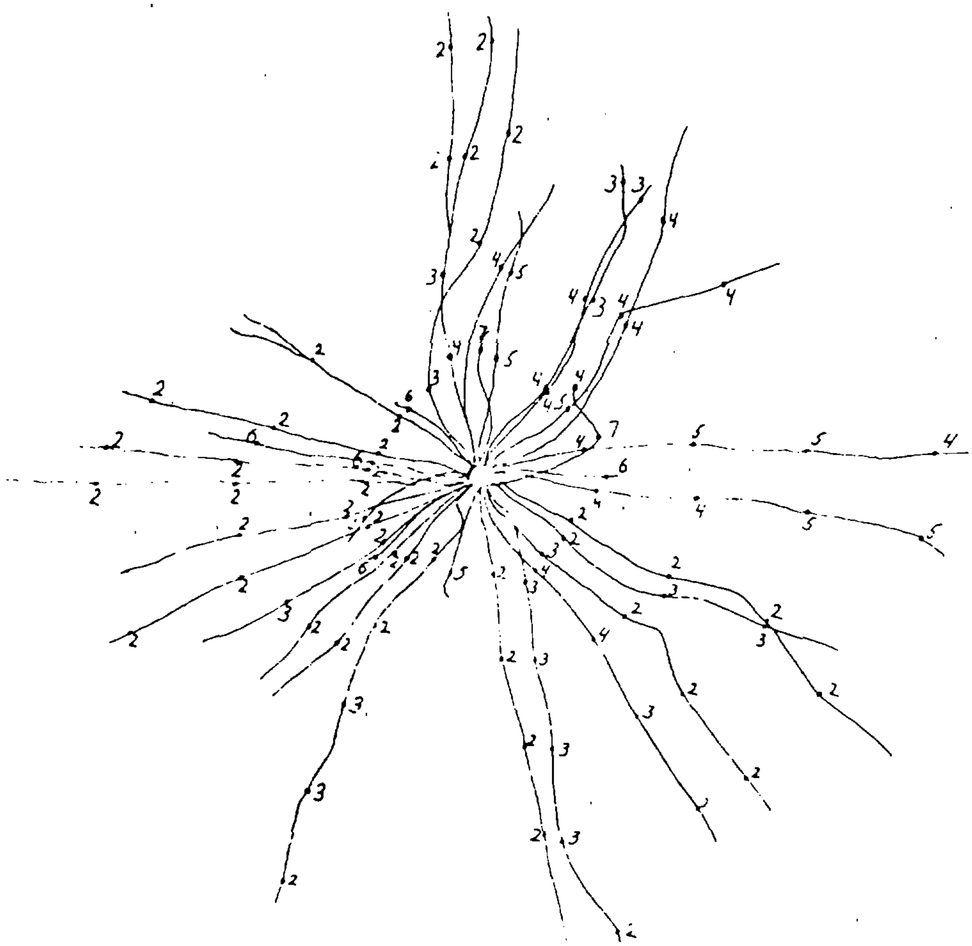

Figure 53. Diagram of Japanese black pine tree B root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

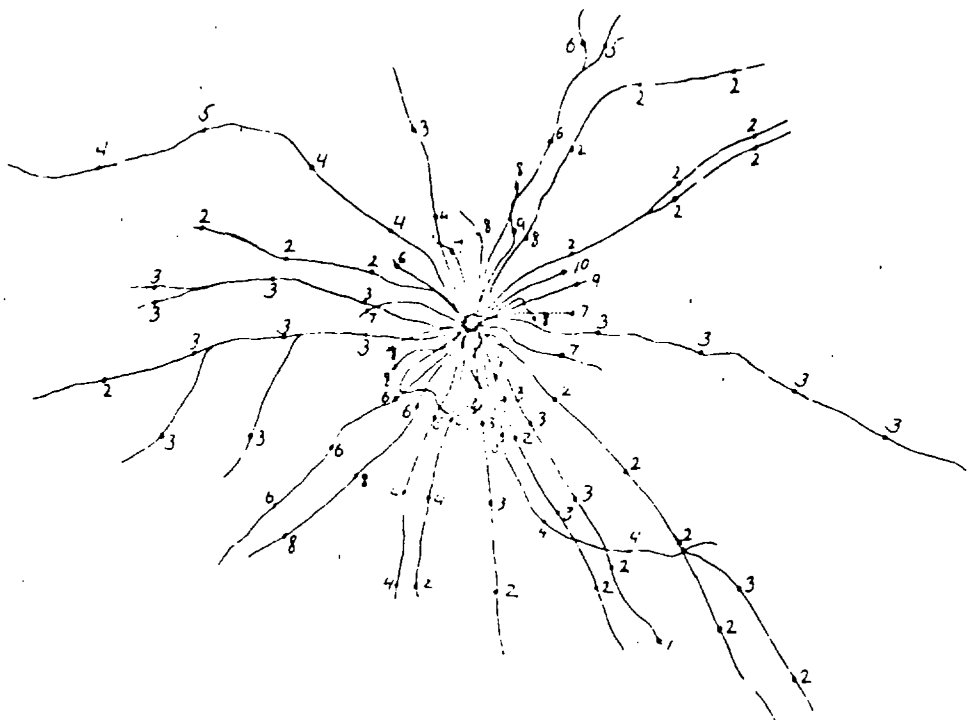

Figure 54. Diagram of Japanese black pine tree A root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

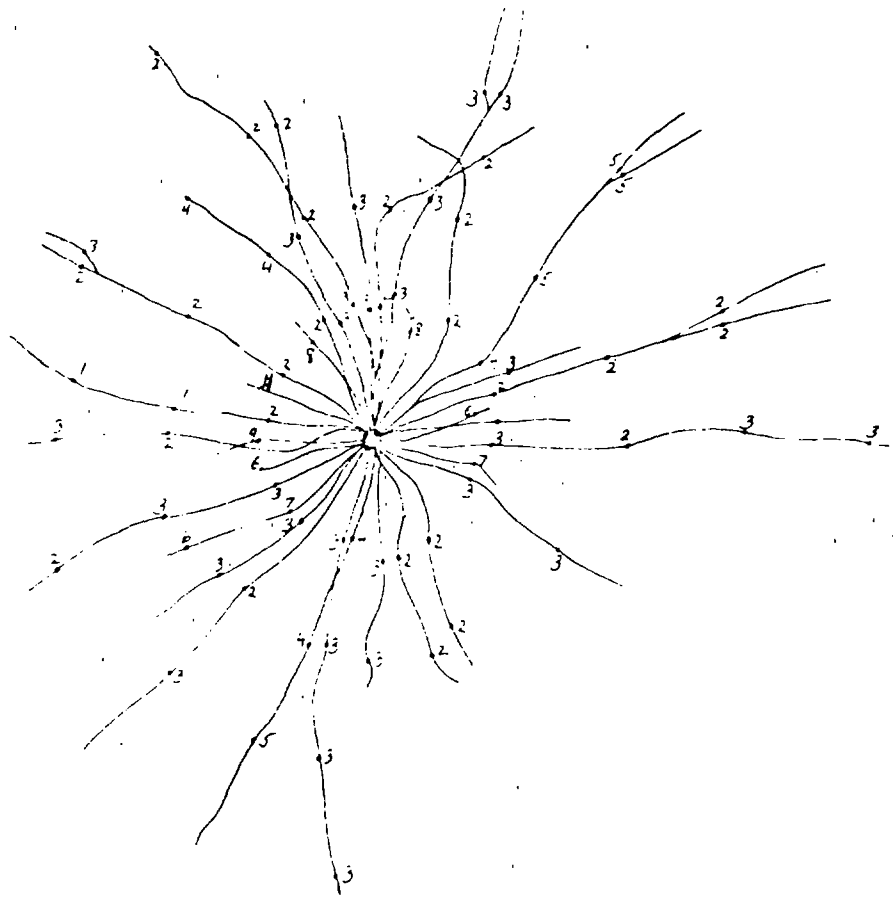

Figure 55. Diagram of Japanese black pine tree B root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

TABLE 53. NUMBER OF 30.5-cm (12-IN) NORWAY SPRUCE ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH: TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO_2 CH_4 AND O_2 CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

		Landfill				Control			
		Tree A		Tree B		Tree A		Tree B	
Soil depth in	cm	# of roots	%	# of roots	%	# of roots	%	# of roots	%
1	2.5	99	83.2a+	3	4.3c	92	86.0a	19	29.2b
2	5.1	18	15.1	26	38.8	12	11.2	24	36.9
3	7.6	2	0.7	25	36.2	3	2.8	14	21.5
4	10.1	0	0	12	17.4	0	0	6	9.2
5	12.7	0	0	3	4.3	0	0	1	1.6
6	15.2	0	0	0	0	0	0	0	0
7	17.8	0	0	0	0	0	0	1	1.6
Total length (m)			36.3		21.0		32.6		19.8
Mean depth (cm)			3.0		7.1		3.0		5.4
Maximum depth (cm)			7.6		12.7		7.6		17.8
CO_2			4.2		5.0		1.1		1.2
O_2			18.1		18.7		19.6		19.8
CH_4			1.1		0.2		0.0		0.0

+ Columns with similar letters have similar root distributions at P<.01 by Chi-Square Analysis.

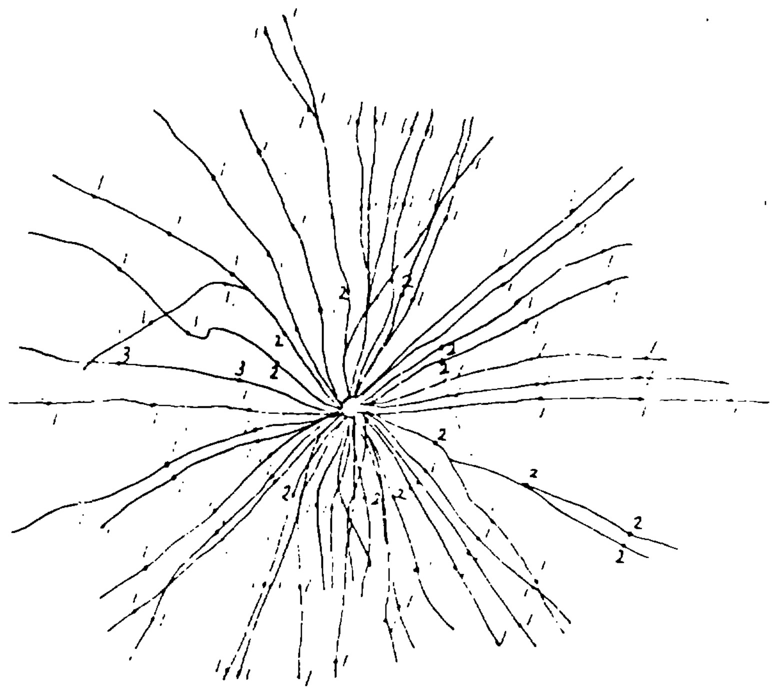

Figure 56. Diagram of Norway spruce tree A root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

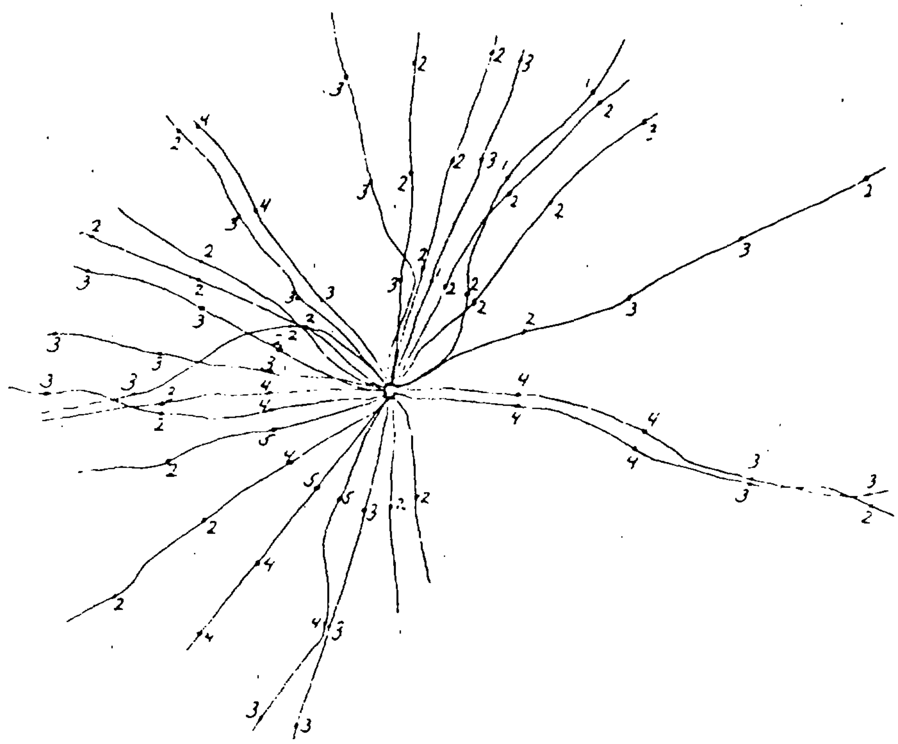

Figure 57. Diagram of Norway spruce tree B root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

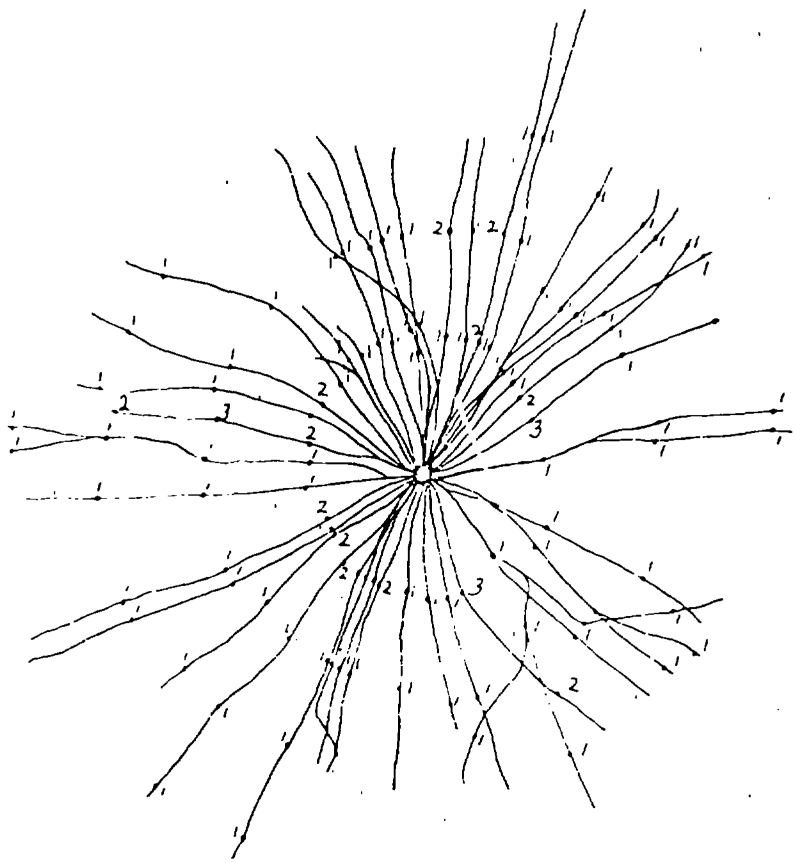

Figure 58. Diagram of Norway spruce tree A root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

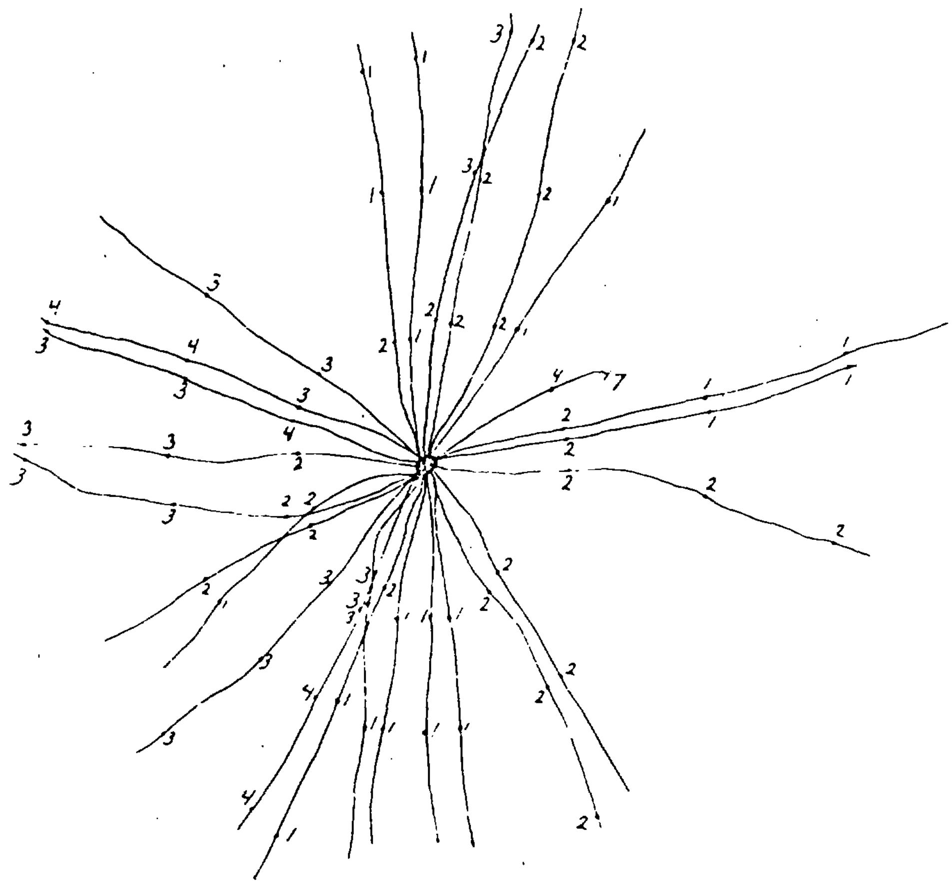

Figure 59. Diagram of Norway spruce tree B root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

Figure 60. Root system of Norway spruce on landfill plot.

Figure 61. Root system of Norway spruce on control plot.

SECTION 7

DISCUSSION

The levels of carbon dioxide (3.9%), methane (0.4%) and oxygen (17.6%) at the 20 cm (8 in) depth in the cover soil of the Edgeboro landfill were found to be similar to levels found in the cover soil of over 67% of landfills surveyed throughout the United States (Leone et al. 1979). Therefore, the principles set forth in this report represent conditions indicative of a large number of landfills in this country.

Relative Viability of Plants

The viability of plants after four years growth on the completed Edgeboro landfill differed among species. By the end of 1979, all the weeping willows, rhododendrons, and euonymus had died on the landfill plot; willows and rhododendrons, obviously having been unable to withstand periods of desiccation characteristic of such sites during mid-summer. The euonymus shrubs on the site which were not girdled by rabbits during the winter of 1977-1978, also appeared to have become desiccated during mid-summer from lack of sufficient soil moisture. Several sweet gum, black gum, bayberry and pin oak died from undetermined causes; landfill gas contamination of the root zone and low soil moisture during mid-July 1978 were suspected as contributing factors in the sweet gum deaths. Since the concentrations of carbon dioxide, oxygen and methane at the 20 cm (8 in) soil depth can reportedly vary from one day to the next, some tree deaths may have resulted from landfill gas migrating into the root zone during periods when gas measurements were not determined; i.e. samples might have been collected on days of lower concentrations. If this were the case, harmful levels of the measured soil gases might not have been recorded. Even if the carbon dioxide and methane levels were considerably higher than the average levels during short intervals between sampling dates, Arthur (1978) indicates that short periods of high landfill gas concentrations may adversely affect tree growth.

More than 60 additional gases have been reported in the anaerobic environment of landfills (Personnel communication, Fred Rice, Reserve Synthetic Fuel, California, 1977) including ethane, propane, phosphine, hydrogen sulfide, nitrogen and nitrous oxides (McCarty 1963; Rovers and Farquhar 1972; Toerian and Hattingh 1966). Some or all of these other gaseous components in addition to carbon dioxide and methane may have migrated into the cover soil in the landfill plot on the Edgeboro landfill and adversely affected plant growth.

Relative Growth of Surviving Plants

Landfill tolerance of the surviving trees was based upon two types of growth measurements (shoot length and stem area increase) taken for each species on both the landfill and control plots. From comparisons of growth on the landfill as percent of that on the control, relative tolerance of landfill conditions depended both on the growth parameter measured and the growing season in which measurements were collected. During the 1978 growing season, black pine shoot and stem growth on the landfill plot compared to the control was better than for any other species (Tables 4 and 5). During 1979, however, shoot growth of black pine on the landfill was fourth and stem growth tenth best of all species as compared to controls. Thus, black pine appeared to be less tolerant of landfill conditions in 1979 than in 1978. Honey locust shoot and stem growth on the landfill plot compared to the control during 1978 were fifteenth and sixteenth in rank, respectively among the species tested; whereas, during 1979, honey locust shoot growth was best and stem growth fifth best of all species tested. Evidently, a tolerance list based on growth measurements during one particular growing season may not necessarily represent a reliable estimate of an overall tolerance to landfill conditions.

Since landfill tolerance also appears to be dependent upon the particular growth measurement in question, one must identify the critical growth criteria for species selection. Since either shoot growth and/or stem growth may be critical for a particular vegetation project, they have been presented in this report both separately and combined, in order to satisfy the needs of a wide variety of individuals.

From comparisons of total amount of shoot growth produced on the landfill from 1976 through 1979 with that in the control plot, ginkgo, black gum and Japanese yew appear to be most tolerant; and green ash, sweet gum and hybrid poplar saplings, least tolerant of landfill conditions (Table 8). From comparisons of percent stem area increase Japanese yew, white pine and Norway spruce seem most tolerant; and hybrid poplar cuttings, hybrid poplar saplings, and green ash, least tolerant of landfill conditions (Table 9).

Since there is reason to believe that no one growth parameter is best suited for comparing tree growth on the landfill with that on the control plot, shoot and stem growth data were combined for the years 1976, 1977, 1978 and 1979 and analyzed as a unit. Two different statistical methods were chosen to analyze the combined growth data in order to rank the test species for overall tolerance to landfill conditions.

One method consisted of averaging shoot growth during 1976 when stem growth was not available and shoot and stem growth for 1977 through 1979 for each species on the landfill plot as a percentage of that on the control plot. The species which produced the greatest amount of shoot or stem growth on the landfill compared to the control received a rank of one. The species which grew most poorly on the landfill compared to the control was ranked last (16th). Thus, seven rank lists were formed and the tolerance rank values from the lists were totaled for each species for an overall landfill tolerance rank (Table 10).

Principal components analyses of shoot and stem data from 1976 through 1979 comprised the second method (Table 11). A factor score was calculated for each species on each plot. The differences in scores between plots were aligned from smallest to largest. The ranking of species from most to least landfill tolerance by this system was similar to the first analytical method. Only two species changed positions dramatically; Japanese yew moved from most tolerant by the first method to eighth according to principal components analysis, and hybrid poplar cuttings moved from eighth in tolerance by the first and least tolerant by the second analysis. As a result of both methods of analysis black gum, black pine and bayberry appeared most tolerant and hybrid poplar saplings, green ash and honey locust least tolerant of landfill conditions.

A final way of assessing relative tolerance to landfill conditions is to total the rank values from each of the aforementioned methods of anaylsis (Table 12). Black gum appears most tolerant and Japanese yew second most tolerant to landfill conditions. It is believed that Japanese yew was ranked very tolerant because growth on the control was inhibited by 'wet feet' conditions.

In all the landfill tolerance lists the species were generally distributed in a similar manner throughout tolerance ranks, i.e. those at the top of one list generally appeared toward the top of the other lists and vice versa.

Stress on the intolerant trees provided by low moisture and/or elevated CO_2 and CH_4 concentrations was reflected in the greater variability in growth on the landfill plot than on the control (Tables 13 and 14). Since tolerant species were apparently more capable than the intolerant species of withstanding the low soil moisture and elevated CO_2 and CH_4 levels of the landfill plot, the lower variability among tolerant trees on the landfill comes as no surprise.

From the previous discussion the following questions must be answered prior to the selection of plant material: Should it produce a quick vegetative cover? Must it grow in a manner similar to trees on non-landfill sites? Should it produce good shoot growth, good stem area increase or both?

Regardless of whether shoot length or stem area measurements are considered, rooted cuttings of hybrid poplar appear to be best suited for vegetating completed landfills if one desires to produce a quick, dense woody vegetative cover regardless of species (Table 15). On the other hand, if one desires to plant a variety of species which would perform as well on a landfill as on non-landfill areas, black gum, bayberry, Japanese black pine and ginkgo appear to be the tree species best suited for this purpose (Tables 10 and 11). Although two of these bayberry and ginkgo both ranked high in these species tolerance lists comparing their growth on the landfill with growth of replicates on the control, their relative absolute growth compared to that of other species on the landfill was the poorest.

From this viewpoint, ginkgo might be one of the least desirable species for landfill plantings. Moreover, since bayberry was the only shrub to survive on the landfill plot and because it rapidly spreads by shallow horizontal rhizomes, bayberry may be a very desirable soil stablizer.

Tolerance of Rapid vs. Slow Growers

Table 12 shows that seven of the eight most intolerant species (those toward the bottom of the list) have been classified as rapid growers; most of the tolerant species are slow growers (Fowells 1965). Apparently, those species with the capacity to grow very quickly, cannot maintain this rapid growth rate on completed landfills, whereas, species which naturally have a slower growth rate can maintain the rate on the landfill comparable to that on the control. Since fast growing trees are likely to withdraw more moisture from the soil, they may become subjected to water stress quicker than the slow growers. Localized low soil moisture tension zones may have existed in the rhizosphere of these rapidly growing trees; however, moisture content measurements were not taken on such a small scale. These data suggest that irrigation is more essential for the establishment of rapid growing trees than it is for establishment of the slow growers. Thus, when growth on the landfill was compared to growth on the control, rapidly growing trees proved intolerant of landfill conditions. However, many of these supposed intolerant (based on landfill growth compared to control) rapid growing species (hybrid poplar rooted cuttings, honey locust and American sycamore) actually produced more absolute vegetative growth on the landfill than other so called tolerant species growing on the landfill.

The generalization is often found in the literature that healthy, vigorously growing plants are susceptible to air pollution damage (Harkov 1979). Although slow growth may be associated with a given stress, it may also be characteristic of a particular plant species and thus allow that species to escape from air pollution damage (Harkov 1979). The present study presents evidence that trees more susceptible to landfill gases (pollution of the root system) are also more likely to be found among the rapidly growing species rather than the slower growers.

Tolerance of Flood Tolerant Species

The characteristic low moisture-holding capacity of landfill cover soils was demonstrated on the experimental landfill plot during the years 1977 and 1978 (Figure 7). Thus, several species may have been stressed by low available soil moisture. Species most likely to be affected by water stress are those which naturally grow in areas associated with a high water table. Five of the eight species (Green ash, honey locust, sweet gum, pin oak, red maple) observed to be landfill stressed in these investigations (Table 12), reportedly cannot tolerate drought conditions (Hook 1973), whereas, only one of the eight tolerant species is reportedly sensitive to droughty conditions. Several of these intolerant species (green ash, red maple, honey locust) may have exhibited sensitivity to landfill soil conditions because they cannot tolerate periods of low soil moisture content and might otherwise have proved to be landfill tolerant if adequate amounts of water had been provided.

A reasonable a priori assumption may be that those species which can withstand periods of flooding, can also tolerate landfill conditions, since both environments generally lack sufficient oxygen for normal root respiration. However, since the soil on the Edgeboro Landfill was often lacking in moisture, these species were probably not afforded the opportunity to exhibit their low O_2-adaptibility mechanisms. Thus, their growth on the landfill was much reduced compared to the control.

Effect of pH on Tolerance

There is evidence for the notion that soil pH levels may affect species tolerance to landfill conditions. During 1978, pH on both the landfill and control plots averaged 4.5. The tolerance (according to 1978 stem increment data) of the five most landfill tolerant species (black pine, Norway spruce, bayberry, white pine and black gum-Table 5) may have been brought about by the ability of these species to thrive in acidic soil (Flannery and Paterson 1964). Accordingly, these five species may have been less affected by the depressed O_2, elevated CO_2 and CH_4 and low soil moisture than other species because the pH (4.5) was close to their optimum requirement (pH=5.0-6.0). Following appropriate lime application in early spring, 1979, the soil pH rose to 6.2 on both plots, representing a much more desirable level for most trees and shrubs. As a consequence, the five low-pH species were no longer concentrated at the top of the landfill tolerance list on the basis of 1979 stem growth (Table 7). Species which were inhibited by low soil pH (e.g. red maple) in 1978, improved their growth on the landfill during 1979 when the pH level was not inhibiting and, therefore, moved up in the tolerance list, thus displacing several of the more acid loving plants like Japanese black pine.

Although stem area increase data provide evidence for the importance of soil pH on landfill tolerance, shoot length data exhibits no recognizable relationship between the two parameters. This indicates that stem area increase may be a more sensitive indicator for the tolerance of woody species to landfill conditions than is shoot length.

Effect of Soil Compaction on Tolerance

High soil bulk density is another factor which may have influenced the response of a number of the test species to the soil environment created on the landfill plot. Hopkins and Patrick (1969) indicate that plants are more adversely affected by high soil bulk densities at depressed soil oxygen levels (<10%) than at normal soil oxygen concentrations (18-20%). Gilman et al, (in press) report that growth of American basswood on completed sanitary landfills is significantly inhibited at high soil bulk density levels. Optimum levels of soil bulk density for a variety of crops vary between 1.3-1.5 g/cc. Since bulk density on the landfill plot during the current investigations was 1.6 g/cc, the lowered oxygen content in the landfill soil may have caused some species to be affected by high soil compaction.

Tolerance of Shallow vs. Deep-Rooted Species

The species which adapted to the landfill plot more quickly (Japanese black pine, Norway spruce) have a shallower and more extensive root system on the landfill than the intolerant species (honey locust, green ash, hybrid poplar) (Table 43). All species produced a shallower root system on the landfill than on the control except Norway spruce. However, the difference in root depth between landfill and control plots was small for black pine and spruce compared to a fairly large difference for the intolerant because they had to produce a proportionally shallower root system on the landfill than on the control than did the tolerant species. This study presents evidence that the root systems of these presently intolerant species are making their way toward the soil surface and may in several years be able to tolerate landfill conditions. Their root system will probably have grown away from the higher carbon dioxide and methane concentrations (and consequently, lower oxygen concentrations) in the deeper soil strata, and will probably require extensive irrigation in order to maintain growth comparable to the control.

Tolerance of Small vs. Large Trees

The enhanced landfill adaptive capabilities of small trees compared to large trees appears to be supported by evidence presented in this report wherein shoot growth for small trees of four (pin oak, green ash, sugar maple, hybrid poplar) of five species tested was equally good on the landfill as on the control, whereas, shoot growth on the large specimens (saplings) was significantly lower ($P<.10$) on the landfill than on the control plot.

Tolerance of Balled-and-Burlapped vs. Bare-rooted Material

Another practice involving root characteristics which may aid trees in becoming adapted to stressed environments is the use of balled-and-burlapped material rather than bare-rooted stock. In this investigation with a single species, sugar maple, balled-and-burlapped trees produced longer shoots and greater leaf volume than bare-rooted trees on the landfill plot, but not on the control plot. Obviously there was some advantage in having a less pruned root stock. There may also have been better mycorrhizae inoculum in the soil ball. However, whether this is a characteristic of one species or whether the results may be extrapolated to other species must be further determined by further experiments.

Tolerance of Irrigated vs. Non-irrigated Plants

Sugar maple was used to assess the value of supplemental irrigation in adapting trees to landfill cover soils. This species generally grew better in the control soil having higher moisture and oxygen contents and lower carbon dioxide than in the landfill. Although supplemental irrigation increased the soil moisture in both plots, irrigated maples produced significantly more ($P<.01$) leaf tissue than non-irrigated trees on the landfill but not on the control during 1978 and 1979. Shoot length was enhanced by irrigation in both plots, but the increase was not statistically significant. Possibly, the failure of irrigation in the control plot to stimulate growth was due to the fact that sufficient rain had fallen during the growing season so that moisture was not a limiting factor for growth of sugar maple on the control as it was on the landfill.

Decreased growth of sugar maples on the landfill plot was undoubtedly due to the combined effects of low soil moisture and slightly elevated soil carbon dioxide and depressed oxygen concentration. Also, the elevated carbon dioxide levels may have caused the production of a shallower root system on the landfill than on the control and, therefore, predispose the maples to drought damage. Gingrich and Russell (1957) report that oxygen and moisture content interact such that at high oxygen concentrations, low moisture content has a more deleterious effect on corn growth than at low oxygen contents. The oxygen concentration in the landfill soil was only slightly depressed, therefore, low soil moisture could have had a strong effect on maple development.

Arthur (197[illegible]) observed an increase in stomatal resistance, and hence reduced transpiration of sugar maples after several days of exposure to simulated landfill gas mixtures. A similar effect was observed in sugar maples growing in the landfill plot (Table 8). Elevated soil carbon dioxide concentrations (7.8%) in the non-irrigated portion of the landfill caused significantly increased stomatal resistance in the sugar maples from late morning until early evening (Figure 9) over that of the trees located on the landfill where carbon dioxide averaged 2.8%. Irrigation throughout the growing season did not significantly reduce the stomatal resistance below that of the non-irrigated area.

Air temperature, relative humidity, and other meteorological parameters are also known to affect stomatal aperature. Multiple regression analysis of diffusive resistance changes during the day showed that temperature and humidity effects accounted for 71% of the variability in the landfill irrigated area (equation 2-page 66) where the carbon dioxide (2.3%) and oxygen (17.[illegible]%) contents were close to that of non-landfill soils. Since only 16% and 0%, respectively, of the variability was explained by these two parameters in the non-irrigated areas with higher carbon dioxide and lower oxygen content the deleterious gas atmosphere and low moisture content of the soil appear to have prevented temperature and humidity from exhibiting an influence on stomatal resistance. Total wind movement from August 9 through August 23 alone accounted for 43% (equation 3) and 53% (equation 4) of the variability in stomatal resistance in the control irrigated and non-irrigated areas, respectively. After wind movement was entered into the equation, no other variable contributed significantly to the remaining variability. On the landfill plot, however, soil oxygen and moisture content contributed significantly to the variability. Apparently, the effects of adverse gas environment and reduced moisture content on stomatal aperature in the landfill plot have overridden the recognized effects of temperature, humidity and wind.

Effectiveness of Gas Barriers

Of the five landfill gas-barrier systems tested, the landfill mound lined with a 30 cm (12 in) clay layer appears to have promoted better growth of American basswood and Japanese yew than the unmodified landfill area. Basswood and yew with the unlined landfill mound was generally greater (but not significantly so) than in the unmodified landfill area (Table 22). In addition, the concentrations of carbon dioxide, methane and oxygen in the two landfill mounds were not significantly different from that in the unmodified control or control mound areas indicating that the mounding of soil functioned successfully in preventing the upward migration of landfill decompositional gases into the root zone of gas susceptible plant species.

Noticeable changes in soil nutrient contents were observed in areas with high landfill gas concentrations. Available soil manganese and iron contents during 1978 and 1979 were high in the clay/vents trench where the oxygen content was lowest (4.3%). Despite this relatively high average oxygen concentration, small pockets of anaerobic soil may have occurred in areas removed from the zone of influence around the gas samplers that may not have been measured. Leone et al. (1979) report that where the oxygen content in landfill soil averaged 4.3%, available manganese content was significantly higher ($P<.05$) than in other areas on the landfill where the oxygen concentration was 16.3% or higher. Data from the current study and the one cited above suggest that low oxygen levels in the landfill soils are associated with high levels of manganese. This is not surprising since high manganese and other micronutrient levels are frequently associated with flooded soils containing little or no oxygen (Ponnamperuma 1955).

An evaluation of the effects of varied soil environments on American basswood growth was made possible because of the variety of soil conditions found in the gas barrier and in other areas on the landfill and control plots. Correlation coefficients were calculated for a number of soil and tree parameters (Appendix B). Soil oxygen, carbon dioxide, potassium, manganese, nitrate content and bulk density were significantly correlated with all four growth parameters: shoot length, leaf weight, root biomass and stem increase. Multiple regression analyses were performed for the tree parameters using the soil gases, moisture content, bulk density, soil temperature and soil nutrient contents as independent variables. The models resulting from this analysis follow:

Shoot length=0.41 + 0.10 ($Mn^{*}-Mn^{**}$) + 0.07 NO_3^{**}

R^2 = 55% equation 4

Leaf weight=0.59 - 0.07 NO_3^{**} - [illegible] 2 Mn^{*}+0.01 ($K^{*}-K^{**}$)-0.2[illegible] (Bulk density X Moisture cont[illegible]). R^2 = 7[illegible]% equation 5

Root biomass=843.79+21.08 NO_3^{**}+ [illegible] (Moisture [illegible] O_2)

R^2 = [illegible] equation 6

Stem cross-section increase=23.51+0.55 NO_3^{**}+0.[illegible]1 ($Mn^{*}-Mn^{**}$)-2.51 (Bulk density X Moisture content). R^2 = 69% equation 7

These models suggest that soil nitrate and manganese levels had a direct effect on growth of the basswood trees.

Carbon dioxide and oxygen levels were also significantly correlated with

*Indicates soil measurement in June 1977.
**Indicates soil measurement in October 1977.

the four growth parameters; however, the correlation coefficients were slightly higher for the soil nutrients; hence, their inclusion in the regression models. The exclusion of the toxic soil gas (CO_2) from the models above does not suggest that they did not directly affect growth. Soil gases at these concentrations have been shown to dramatically affect vegetative growth (Flower et al 1978, Leone et al 1979). However, the high correlations between soil oxygen and soil nitrate levels (r = + 0.63) and between soil oxygen and soil manganese levels (r = -0.80) suggest that the oxygen concentration has dramatically affected the levels of nitrate and manganese in the soil. Although the data are not necessarily conclusive, we can state, as did previous investigators, (Hoeks 1972), that the presence of methane gas in soils is probably associated with microbial activity through which some plant nutrients, particularly nitrogen compounds and trace metals are made available. It is within the realm of possibility that some trace element (possibly manganese or iron), essential to plants at low concentrations, could be reaching toxic levels in soils contaminated by methane.

A reason for the absence of a soil moisture component in the equations describing shoot length variation may be that the basswoods concluded most of their shoot growth by early June, whereas, soil moisture was considered adequate or non-limiting for shoot growth until mid-June. On the other hand, the leaves continued to expand through early July and thus lack of soil moisture was able to exhibit an effect on leaf weight resulting in the inclusion of moisture content in the equation (eq. 5) explaining variability in leaf weight.

The effects of soil moisture on stem and leaf growth depended on the soil bulk density level as shown by the cross-product term (bulk density X moisture content) in both models (eq. 5 and 7). For instance, at a high bulk density (1.8 g/cc), the higher soil moisture in the unmodified control area compared to the unmodified landfill area (Table 27), resulted in a significant increase in stem growth in the control (Table 24). On the other hand, at a medium bulk density (1.6 g/cc), the significantly higher soil moisture in the control trench compared to the clay trench, resulted in a non-significant increase in stem growth. Furthermore, at the low bulk densities (1.3 g/cc) found in the clay/vents and gravel trenches, a higher soil moisture content is associated with the poorest stem and leaf growth indicating the possibility that increasing soil moisture at low bulk densities may be detrimental to plant growth. More likely, low oxygen and/or high carbon dioxide contents inhibited growth in the clay/vents trench.

Soil oxygen and carbon dioxide are both significantly correlated with basswood growth (Appendix C and both can reportedly cause a large effect on plant productivity (Leone et al 1979). Possibly, the high carbon dioxide and low oxygen concentrations in the clay/vents trench have affected basswood growth so that less water was removed from the soil by the trees in this area. Water is also a product of refuse degradation (Farquhar and Rovers 1972) and may travel through the soil along with the gases produced during decomposition. Thus, the higher soil moisture in the clay/vents trench appears to be a result of rather than a cause of poor growth. Therefore, the significance of the bulk density X moisture content term in the two models appears to depend solely on the high soil moisture in the clay/vents trench associated with very poor basswood growth.

In order to evaluate the effect of the landfill environment on the total amount of nutrients accumulated by the basswoods in each test area, average weight of leaves per branch was multiplied by tissue nutrient concentration. The differences in total uptake among the nine areas were analyzed in two ways: first by using the total nutrient content and second by adjusting the nutrient means for bulk density and root biomass differences between areas.

Soil bulk density differences between areas resulted from differential soil compaction caused by the use of heavy equipment necessary in preparing the site for planting, therefore, neither the refuse, nor any products from it, had any influence on bulk density. Considering this and the correlation between bulk density and nutrient uptake, removal of the effect of bulk density on nutrient uptake allows for a better appraisal of the effects of landfill-influenced soil conditions on nutrient uptake. Root biomass differences between areas were influenced by landfill conditions (Gilman 1978). High positive correlations existed between basswood root biomass (even though it was measured quite crudely and varied considerably within each area) and total uptake of all eight nutrients measured. When the effect of root biomass on nutrient uptake was removed from the analysis by Analysis of Covariance, a measure of the efficiency of uptake at the root surface was obtained. This efficiency is an evaluation of the ability of a given section of root surface to absorb nutrients, regardless of the total amount of root surface available for absorption.

The most striking difference between the unadjusted (raw data) and adjusted means (efficiency after removal of bulk density and root biomass component for nutrient uptake per branch) is that after adjusting, nutrient accumulation in the gravel/plastic/vents trench and clay mound was no longer significantly greater than that in the unmodified experimental screening area, indicating that root biomass and bulk density had a great influence on nutrient accumulation. Consequently, basswoods in both landfill mounds, the gravel trench and the clay trench accumulated the eight nutrients no more efficiently than in the landfill screening area. In the clay/vents trench, nutrient uptake efficiency was actually significantly reduced. The carbon dioxide and methane gas concentrations were significantly greater ($P<.01$) and oxygen significantly lower in this area than in all other areas. Apparently, soil carbon dioxide can reach 7% and oxygen can drop to 16.3% with no effect on nutrient uptake efficiency. However, when the carbon dioxide concentration reached 22.8% and oxygen, 4.3% (clay/vents trench), nutrient accumulation efficiency was significantly reduced (Table 30).

Plants grown in soils low in oxygen often accumulate le[illegible]tassium [illegible]an those grown in soil with an adequate oxygen supply (Hammond 1955). If less potassium is taken up by the plant, then relatively more potassium should be left in the soil. This was true for American basswood in terms of concentration of potassium in the leaf tissue (Table 25 and total potassium uptake per branch (Table 26). More potassium was left in the soil (i.e. the potassium value in June minus that in October was small) in those areas where basswood leaf weight and total potassium uptake were low. This is represented in equation 2 by a positive coefficient for the potassium in June minus potassium in October effect in the model describing leaf weight variability. The oxygen concentration in two of these poor growth areas (clay vents and clay trenches) was lower than in any of the other areas. Apparently the low oxygen, and/or high carbon dioxide, contributed somewhat to the low potassium uptake of the basswood growing in these trenches, resulting in the small change in soil potassium from June to October.

Foliar concentrations of manganese, nitrogen and potassium were significantly reduced ($P<.05$) in basswood trees growing in the area of highest carbon dioxide and lowest oxygen concentration (clay/vents trench). Similar phenomena were observed by Leyshan and Sheard (1974), i.e. concentrations of nitrogen, phosphorus and potassium were reduced in barley tissue grown in oxygen-deficient soils. Concentrations of nitrogen and potassium were also reduced in avocado (Labanauskas et al. 1968) and potassium was reduced in slash pine (Shoulders and Ralston 1975) when the plants were subjected to reduced oxygen concentrations.

Plants grown in sewage sludge treated soil where the available manganese is often quite high (e.g. 141 ppm) contain significantly higher concentrations of manganese relative to plants grown in non-sewage sludge treated soil. Since literature concerning the effects of low oxygen combined with high soil manganese on accumulation of manganese in tree tissue is wanting, interpretation of the decreased manganese concentration in basswood leaf tissue is at best, speculative. At first glance, lack of oxygen in the soil, causing disruption in respiratory activity in the root system and impairing manganese uptake appears to be an attractive explanation since oxygen level was positively correlated ($P<.05$) with tissue manganese content. However, concomitant with low soil oxygen are high carbon dioxide content, high temperature and on several occasions high methane and possibly other gases in lesser amounts such as hydrogen sulfide (H_2S). Hydrogen sulfide was not measured in the present study; however, detrimental effects of H_2S on root formation and activity have been reported (Hollis 1967, Hollis et al. 1975). Several authors working with the mechanisms of toxicity have indicated that the presence of H_2S may limit nutrient uptake (Joshi et al. 1975, Ponnamperuma 1975). There have been no reports of the effects of temperature or methane on nutrient uptake.

Tissue calcium concentration was significantly lower for the two areas (clay/vents and clay trenches) where oxygen was lowest and carbon dioxide highest in content. Soil temperature was also higher in the clay vents trench than in all other areas. Regression analysis showed that the temperature during the growing season was highly correlated (R^2=+[illegible]) with calcium concentration (Appendix C). These results are supported by Burstrom (195[illegible]) and Neilson (1971) who separately found that the soil calcium level required to maintain good wheat growth increased with increasing soil temperature from 20°C to 30°C. When corn roots were exposed to cyclic temperatures, they reacted almost identically to the response corresponding to the maximum temperature alone (Rattan 1974). Consequently the correlation between some aspects of growth (i.e. calcium, copper and iron leaf tissue concentration) and highest temperature is not suprising.

Only one of the nutrient elements measured, iron was more concentrated in the clay/vents trench than in any other area ($P<.05$). This area contained the lowest oxygen concentration (4.3%) throughout the entire growing season. It is reported that prolonged low oxygen concentrations brought about by flooded soil reduce iron making it more available to plants (Ponnamperuma 1955) and perhaps causing it to reach toxic levels (Ponnamperuma 1955). Low oxygen alone or in conjunction with flooded soil has also been associated with an increase in iron content in avacodo seedlings (Labanauski 1968). Whether or not iron was taken up by the basswood trees in quantities large enough to cause a toxic response is not determinable from the present study. These data suggest that landfill gases are at least partially responsible for influencing the total productivity and depth of penetration of the American basswood root system and are in agreement with previous work (Gilman 1978) which suggests that high gas concentrations are partially responsible for a decrease in root biomass of trees growing on landfills.

Root Growth in Landfill Cover Soil

Table 43 shows that although total root length and maximum penetration depth were decreased by landfill gases in the unmodified landfill and clay/vents trench areas; average root depth was apparently not reduced in the clay/vents trench where the gases reached their highest levels (22.8% CO_2, 12.0% CH_4), but significantly reduced in the non-trench landfill area where the gas concentration was second highest (8.1% CO_2, 5.8% CH_4). This apparent incongruity can perhaps be explained by the limited root growth in the clay/vents trench, i.e. roots may not have had enough time to grow toward the soil surface before the trees died and thereby avoid the high landfill gases due to the inhibition of growth by the gases or other soil factors early in the growing season.

Carbon dioxide concentration was significantly higher at the 20 cm soil depth in the un-modified landfill area than in any other area except the clay/vents trench. The majority (66.7%) of the roots in the non-trench landfill area extended toward the surface and proliferated there, resulting in the shallowest ($P<.05$) average root depth (7.4 cm) of all areas. It is believed that with the high landfill gas content of the clay/vents trench at the 20 cm soil depth, (22.8% CO_2, 12.0% CH_4) and/or low oxygen content (4.3%), roots cannot grow to avoid this gas environment, but when the conditions are less severe, i.e. the unmodified landfill area (8.1% CO_2, 0.9% CH_4 and 18.5% O_2), American basswood is capable of extending all of its root system 15.3 cm into the soil. Where the gas content at 20 cm was 1.0% CO_2, 0.0% CH_4 and 19.5% O_2, average root depth was 24.4 cm. Results for basswood (Gilman 1978) corroborate those for Japanese black pine, Norway spruce, hybrid poplar, honey locust and green ash discussed previously.

In order to further investigate the effects of high and low landfill gas (CO_2 and CH_4) concentrations on vertical root distribution in landfill cover soil, seedlings and saplings of hybrid poplar and green ash (one replicate of each from a relatively high-gas area and one from a relatively low-gas area on the landfill) were excavated and mapped. Two replicates of each were also excavated on the control for comparison (for a total of eight trees on each plot). Root distribution was significantly shallower ($P<.05$) in the high-gas areas than in the low-gas landfill areas for both seedlings and saplings of these two species. All landfill trees of both species had significantly ($P<.05$) shallower root systems than trees growing in the control plot.

The two factors which differed most between plots were soil gas concentrations and soil moisture content. Carbon dioxide, methane and oxygen concentrations at the 20 cm depth on the landfill (CO_2=3.9%, CH_4=0.4%, O_2=17.6%) were significantly different ($P<.01$) than on the control (CO_2=1.0%, CH_4=0.0%, O_2=19.9%). Soil moisture content averaged 9.0% on the landfill and 11.5% on the control. Since areas on the landfill plot where trees were excavated differed in gas concentration but were similar in moisture content, the shallower root system in the high-gas areas probably resulted from the difference in gas concentration rather than in moisture content. However, differences in root depth between landfill trees and the control trees could have resulted from landfill gas contamination and/or lower soil moisture levels on the landfill than on the control. Few landfill cover soil environments are characterized by low soil moisture content alone (Flower et al); most are associated with elevated levels of carbon dioxide and methane, depressed oxygen concentration, low soil moisture and a variety of other undesirable qualities.

Evidence has also been produced by these studies to suggest that species with a natural propensity toward producing shallow root systems (Japanese black pine, Norway spruce) (mean depth approximately 9 cm and 4 cm respectively on control plot) grew very well in landfill cover soil. Deeper rooted species (green ash, honey locust-mean root depth on control 14.7 and 16 cm respectively) were forced to respond to the landfill stresses through development of surface roots, when deeper roots are the norm and, therefore, grew less vigorously on the landfill than on the control plot.

Apparently, a desirable landfill species should have, in addition to low-oxygen tolerance, one of two rooting characteristics: either a naturally shallow root system or the ability to adapt from a characteristically deeper to a relatively shallower root distribution in order to avoid the deeper adverse soil gas atmosphere. Since only one (black gum) of the seven reportedly flood tolerant species (black gum, bayberry, American sycamore, red maple, green ash, honey locust, sweet gum) proved to be relatively tolerant of landfill conditions (Table 12), the respiratory mechanism responsible for allowing these species to survive in low oxygen environments, operating normally in a water-saturated environment, may not have functioned properly in the low moisture conditions of a landfill cover soil.

Gilman (1978) has previously reported that small trees may be more capable of adapting to landfill conditions than large specimens. In the current root distribution studies, roots of the hybrid poplar sapling (large tree) in the high-gas landfill area were unable to grow at the greater soil depths (30 cm). Only four roots remained alive at the time of excavation (October 1979) and these grew upward from approximately the 20 cm to the 5 cm soil depth. These roots appeared to have reached the soil surface very rapidly because the angle of the roots to the horizontal was rather steep compared to the angle for roots of the similar-sized poplars in the low-gas area. Many of the latter roots appeared to be growing toward the soil surface; whereas, few roots of the large poplars on the control plot grew from deeper to shallower soil depths, many roots actually grew deeper into the soil.

The roots of hybrid poplar trees planted as cuttings (small trees) in the landfill soil also grew toward the soil surface; whereas, roots of small poplars on the control plot did not extend toward the soil surface. However, the rooted cuttings were planted with a very shallow root system, and, therefore, had to adapt less than the poplars planted as saplings which began with a much deeper root system and were more likely to encounter higher landfill gas concentrations than the more shallow roots of the poplar cuttings.

Unlike small-sized hybrid poplars, small green ash seedlings did not appear to adapt to landfill conditions to a better degree than larger specimens. Roots of both seedlings and saplings of this species appear to have adapted to the landfill soil conditions in a manner very different from hybrid poplar. Whereas, poplar roots originating at the deeper soil stratas on the landfill (20-30 cm) made their way upward as they elongated, the deeper green ash roots did not reach for the soil surface but, instead remained at the original depths where growth continued in a stunted fashion. Ash roots can reportedly tolerate low oxygen environments (Gill 1970). Ash roots in this study, therefore, have apparently tolerated adverse landfill gas concentrations (CO_2=13.1%, CH_4=7.3%, O_2=12.3%). Even so, a large portion of the roots in the high-gas area sprouted from the root collar in the top 2.5 cm of soil (Figure 34), thus evincing a shallow root gas avoidance mechanism different from that of hybrid poplar.

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SHOOT AND STEM GROWTH RATES [illegible]

The graphs in this appendix represent shoot and stem growth rates for each species on the landfill and control plots. The species are arranged in descending order of relative tolerance to landfill conditions according to Table 12.

Legend

Shoot length = average shoot growth of all living replicates from 4 shoots per tree during [illegible] (the longest shoot plus the 3 other longest shoots) and from [illegible] shoots during [illegible], 19[illegible] and 19[illegible].
Year = year during which measurement was collected.
Percent stem increase = percent cross sectional increase at heights above ground specified in Table 2 from March to October of the specified year.

Each species' graph can be found on the following pages:

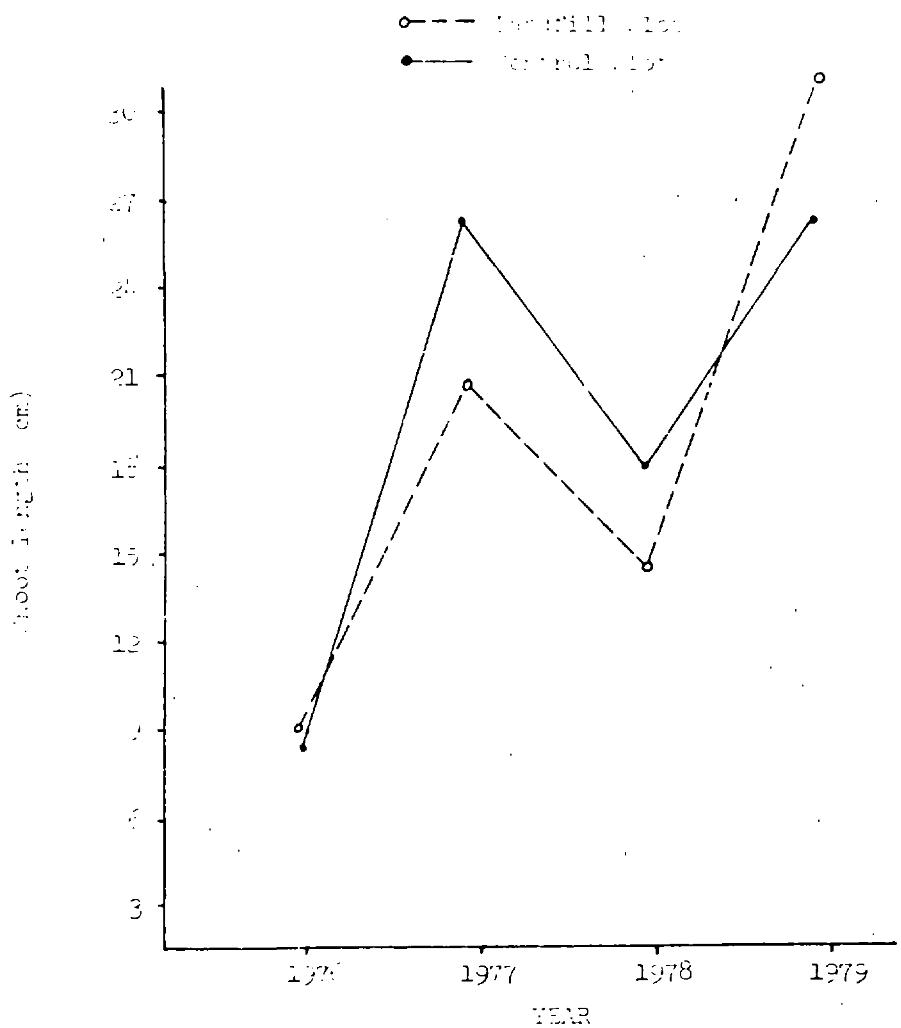

Figure A-1. Black gum shoot length on landfill and control plots from 1976 through 1979.

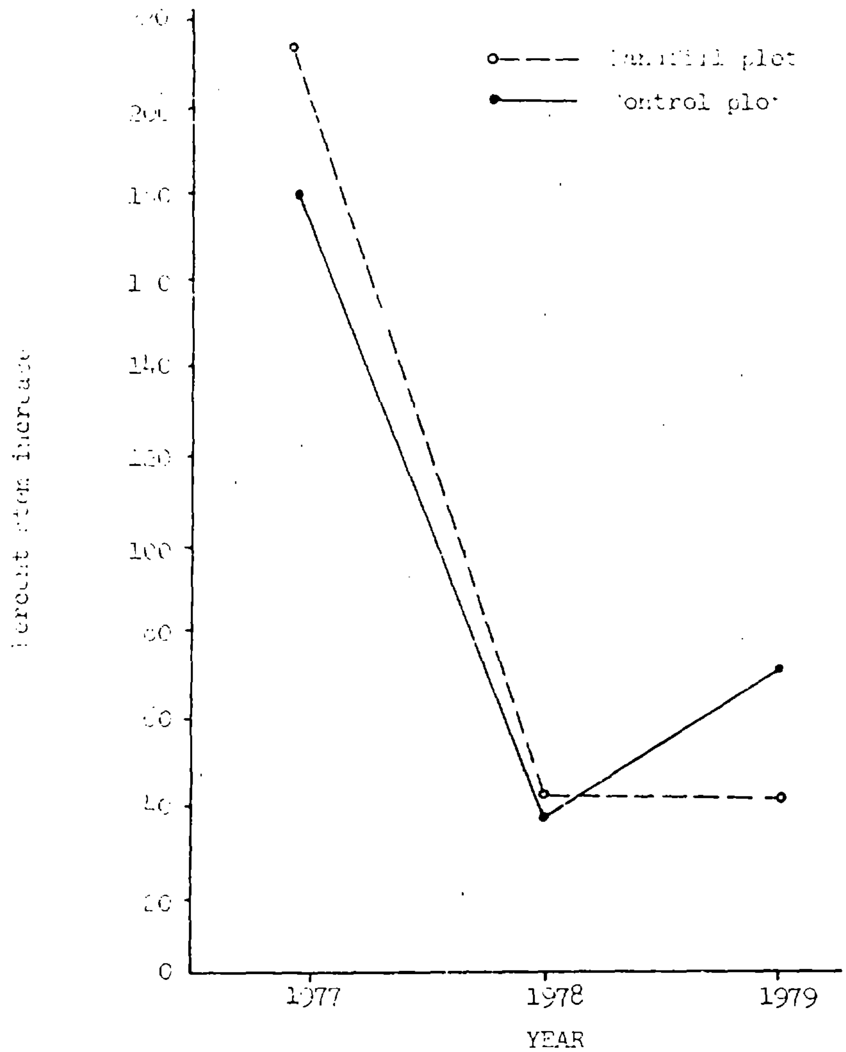

Figure A-2. Black gum percent stem increase during the years 1977 through 1979.

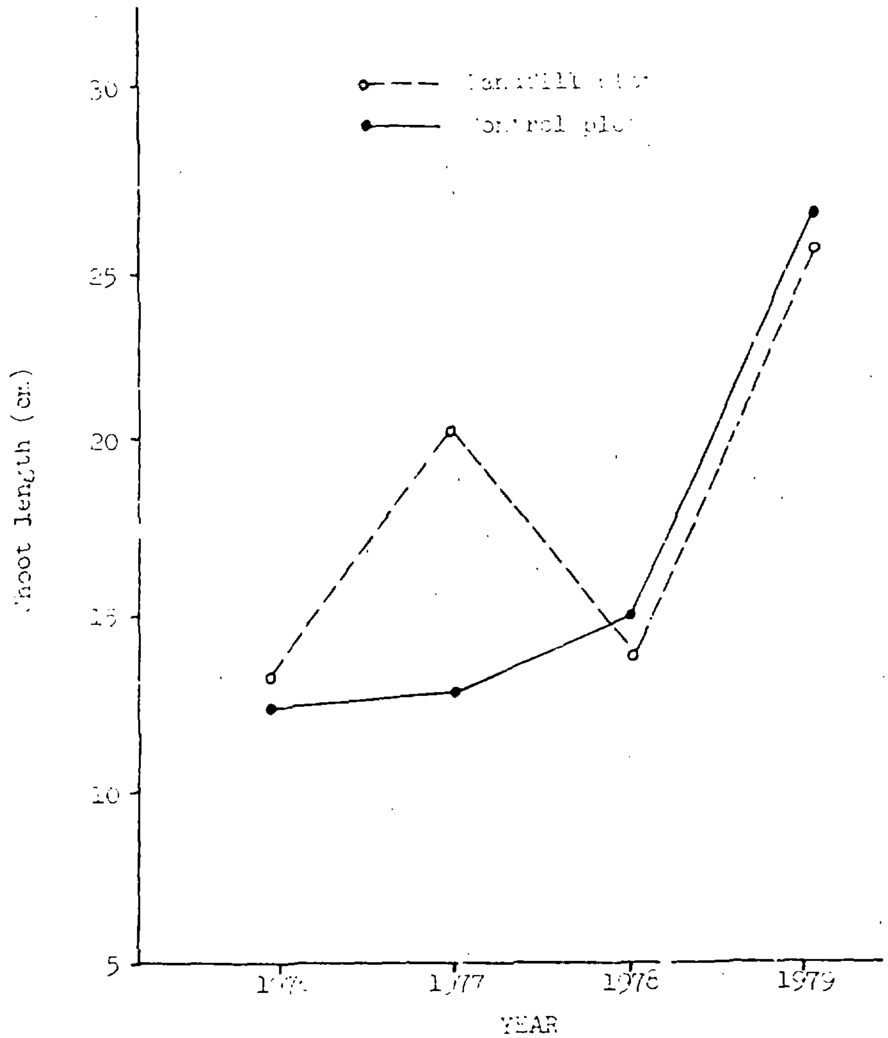

Figure A-3. Japanese yew shoot length on landfill and control plots from 1976 through 1979.

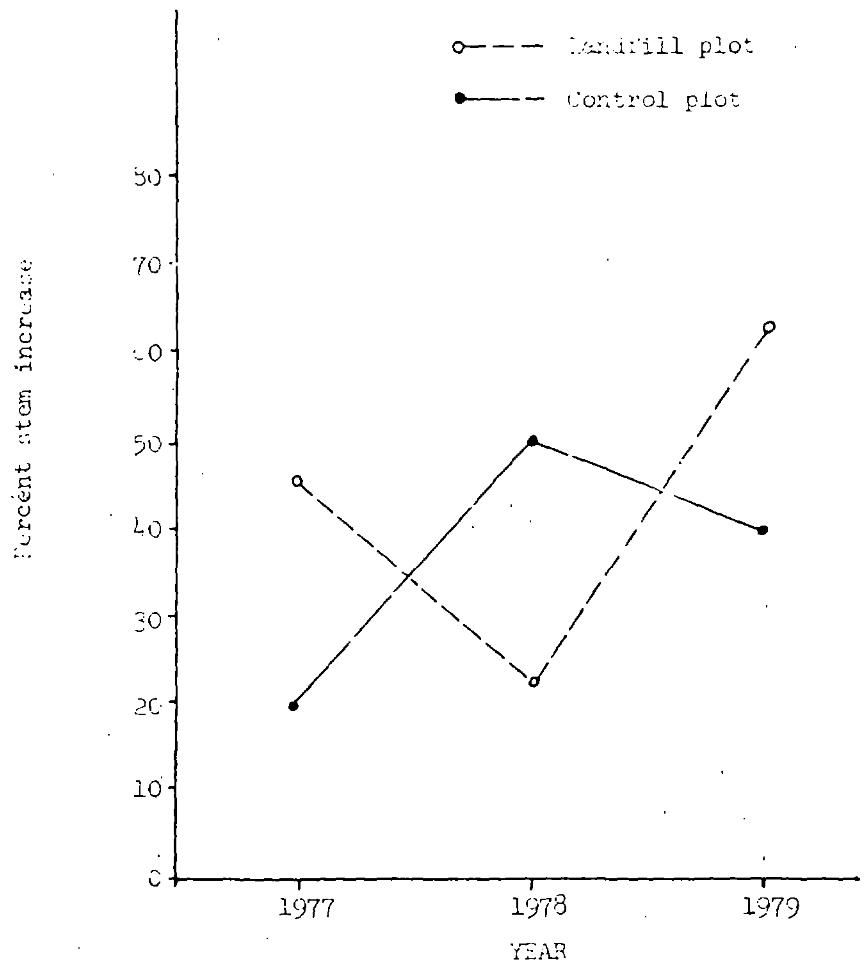

Figure A-4. Japanese yew percent stem increase during the years 1977 through 1979.

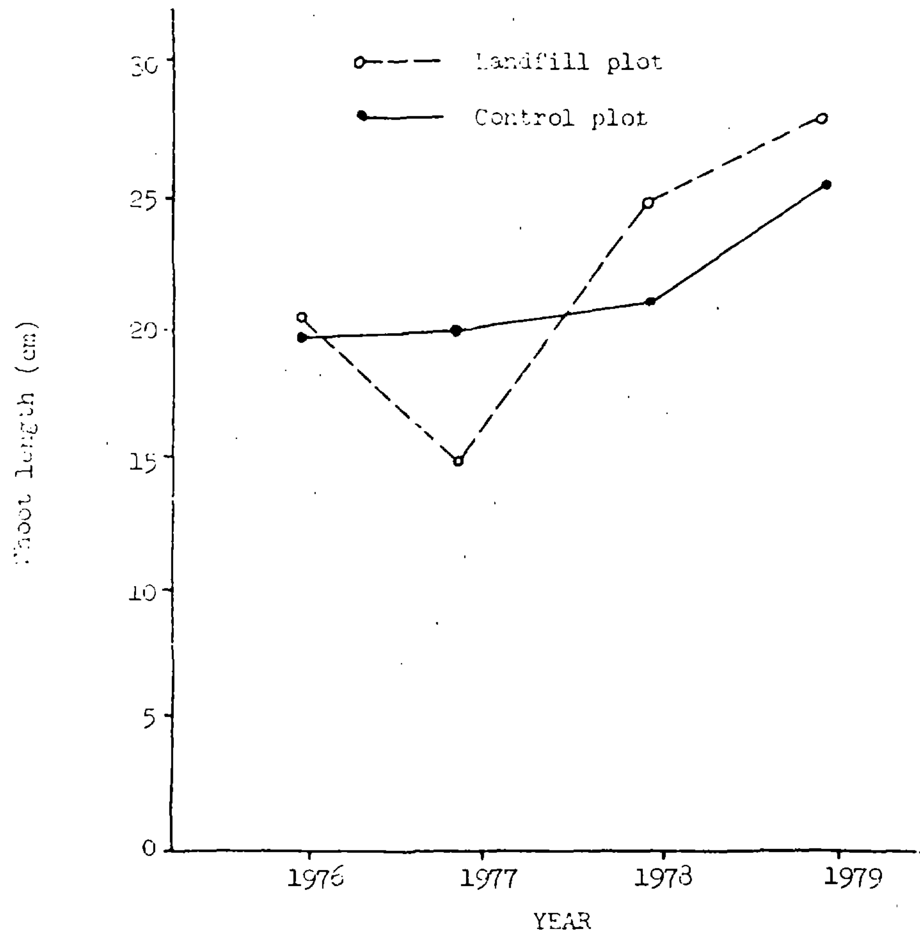

Figure A-5. Japanese black pine shoot length on landfill and control plots from 1976 through 1979.

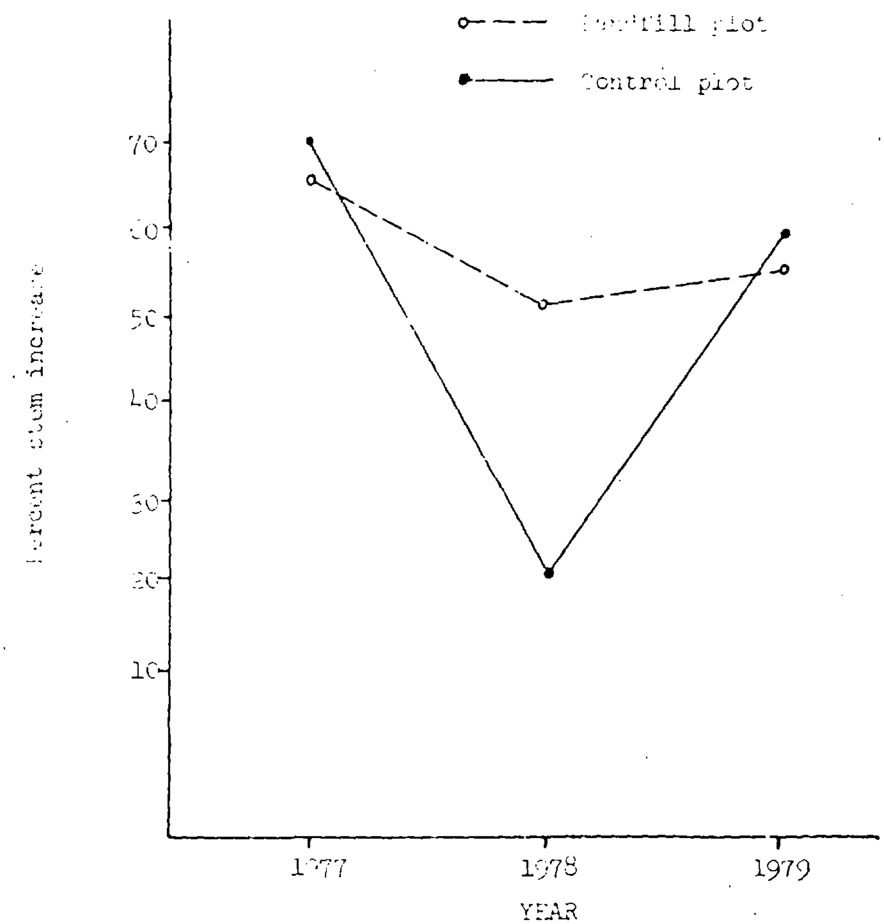

Figure A-6. Japanese black pine percent stem increase during the years 1977 through 1979.

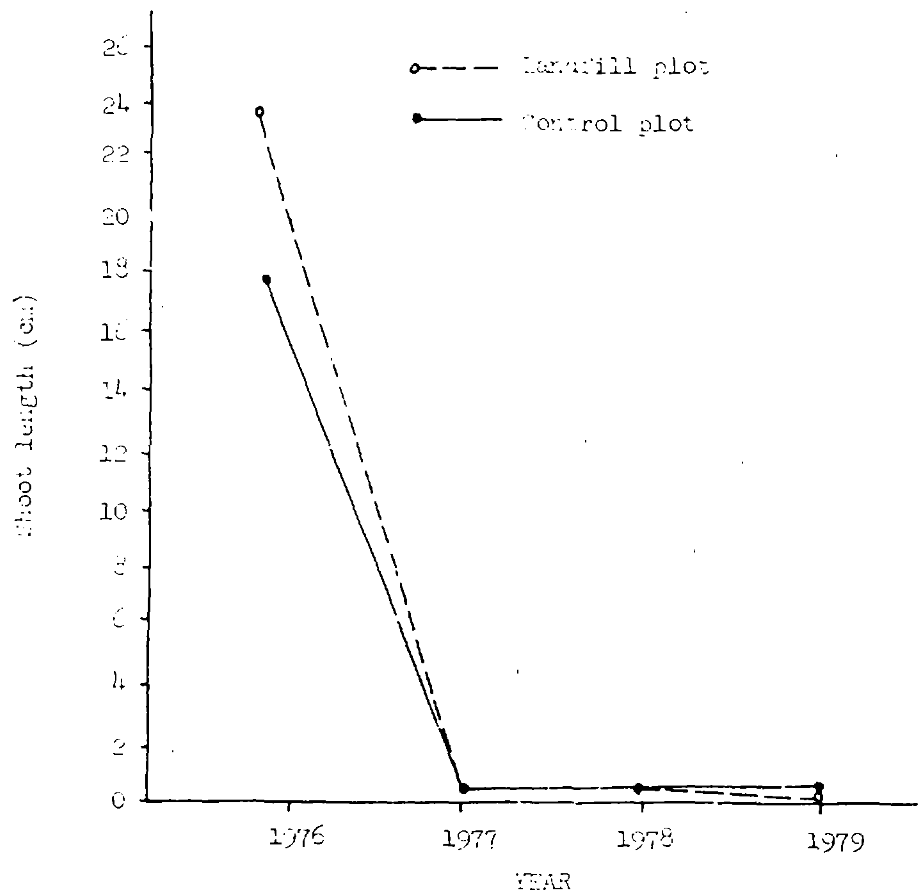

Figure A-7. Ginkgo shoot length on landfill and control plots from 1976 through 1979.

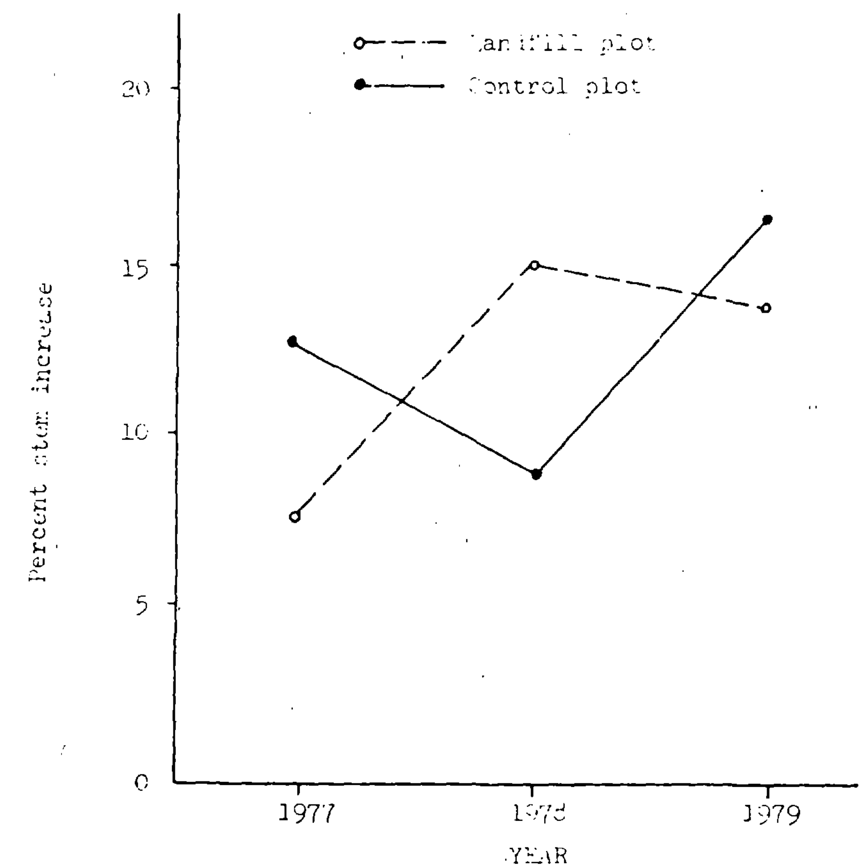

Figure A-8. Ginkgo percent stem increase during the years 1977 through 1979.

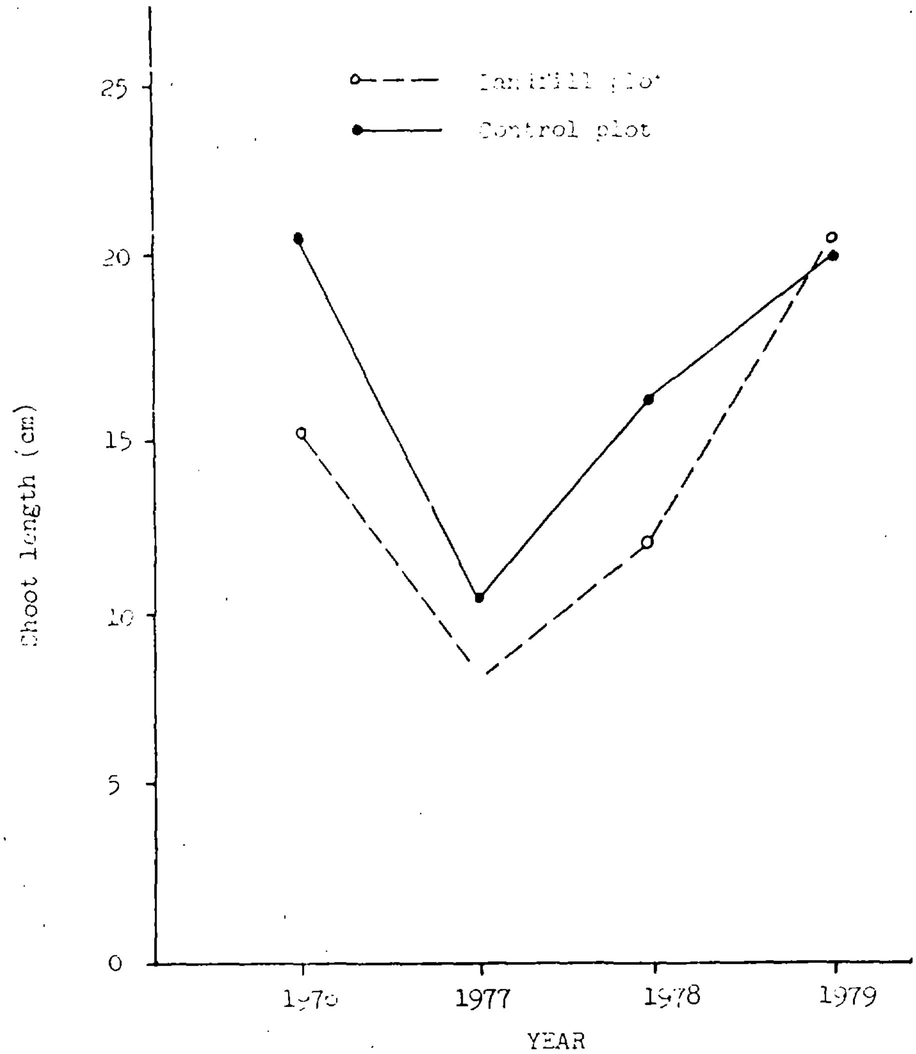

Figure A-9. White pine shoot length on landfill and control plots from 1976 through 1979.

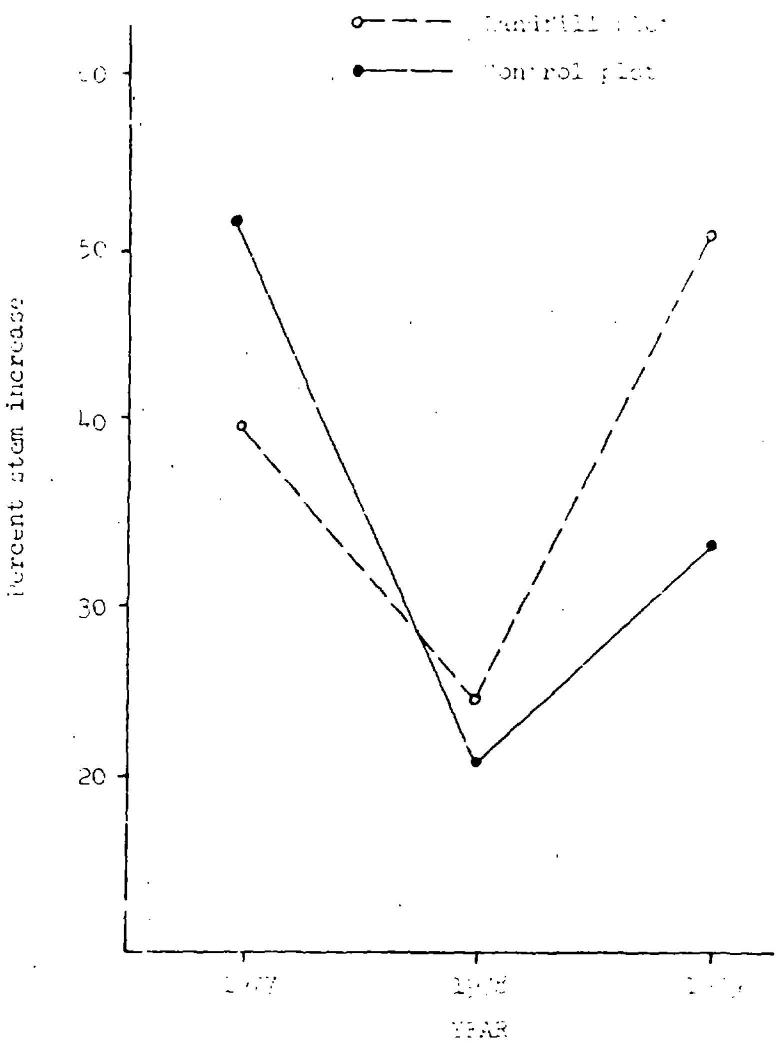

Figure A-10. White pine percent stem increase during the years 1977 through 1979.

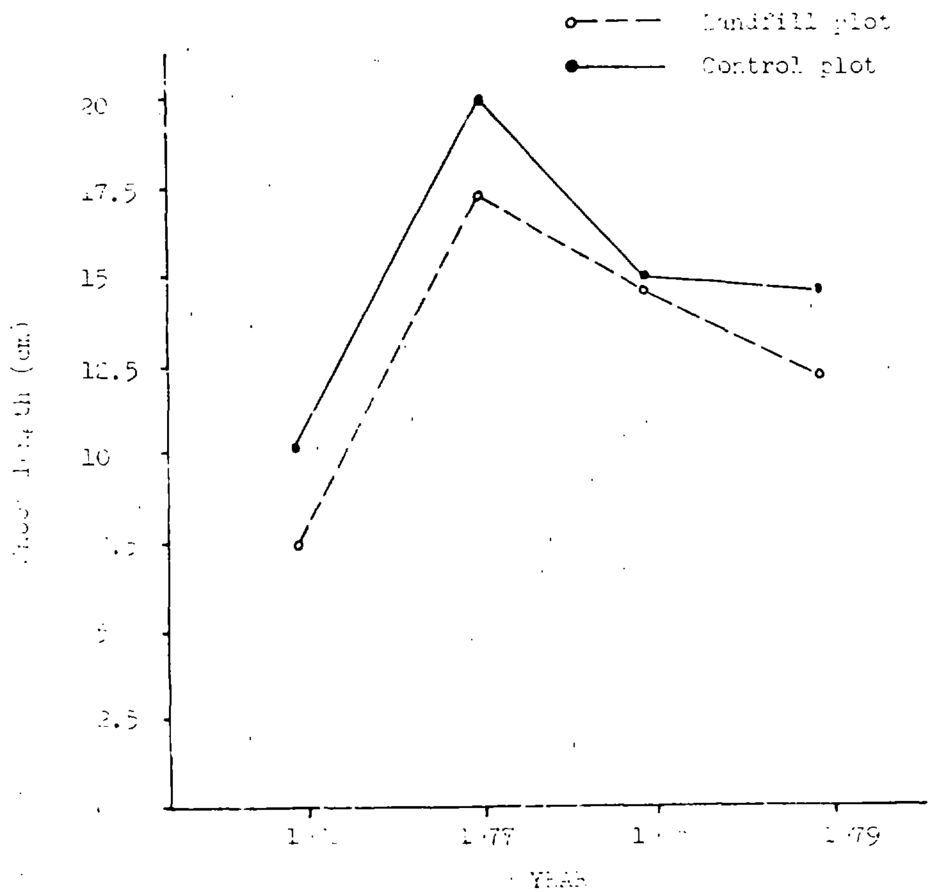

Figure [illegible]-11. Bayberry shoot length on landfill and control plots from 1976 through 1979.

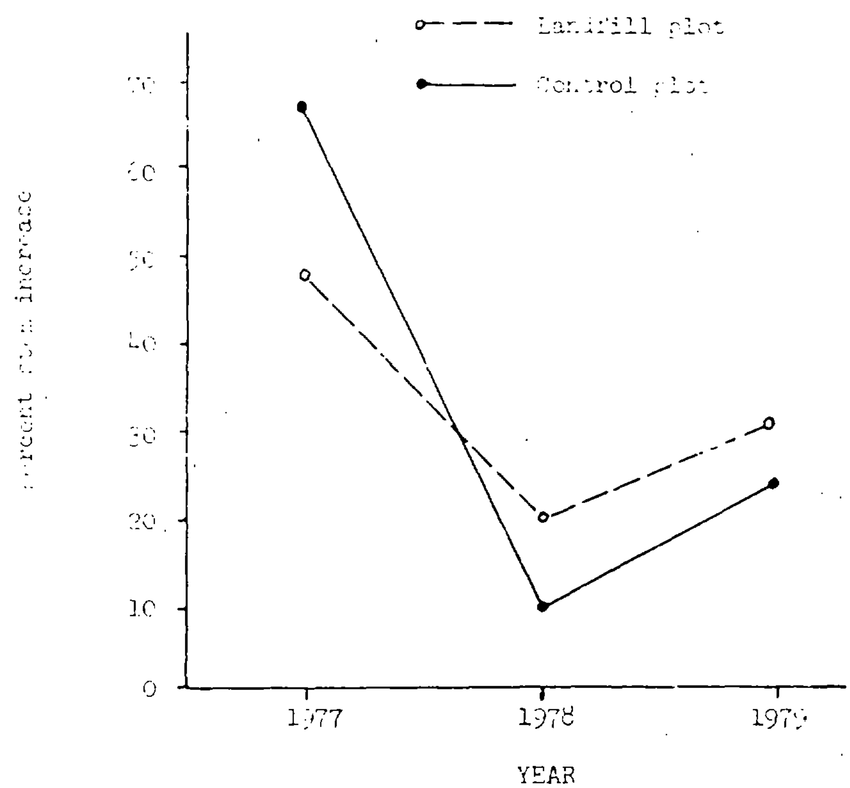

Figure A-12. Bayberry percent stem increase during the years 1977 through 1979.

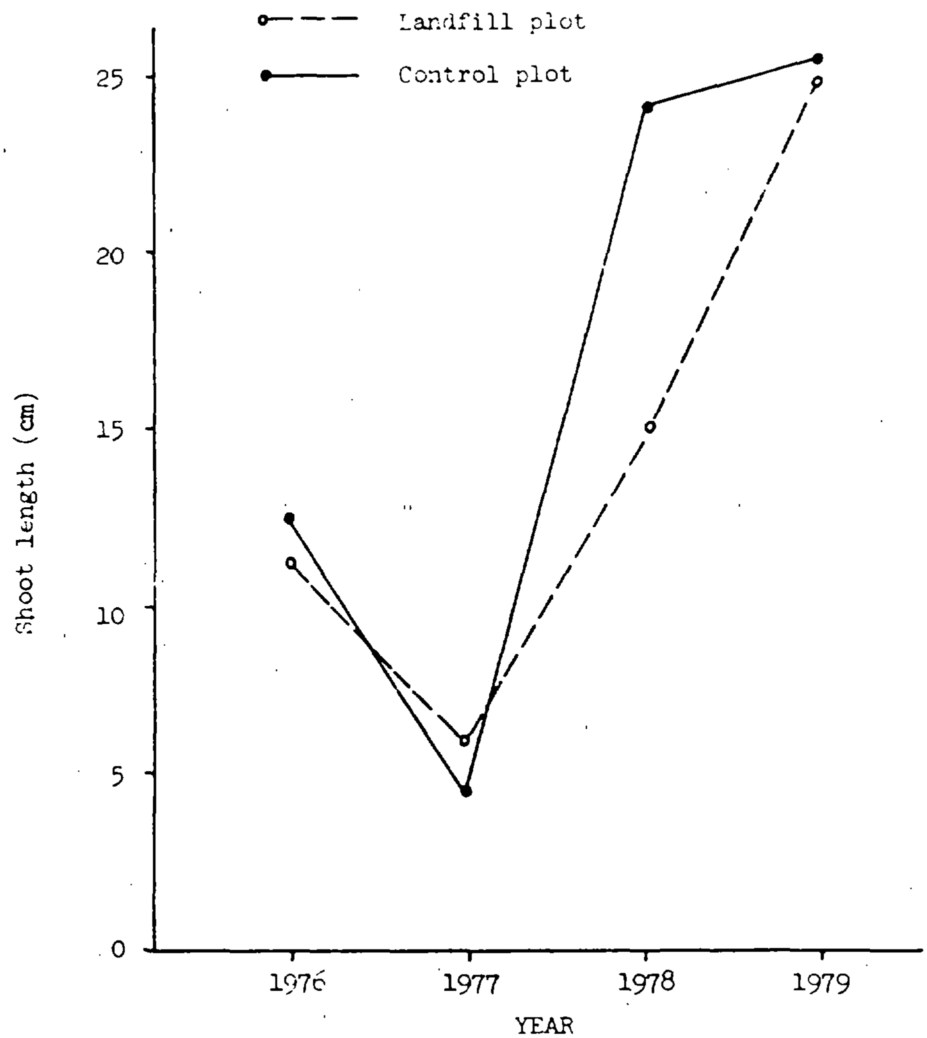

Figure A-13. Norway spruce shoot length on landfill and control plots from 1976 through 1979.

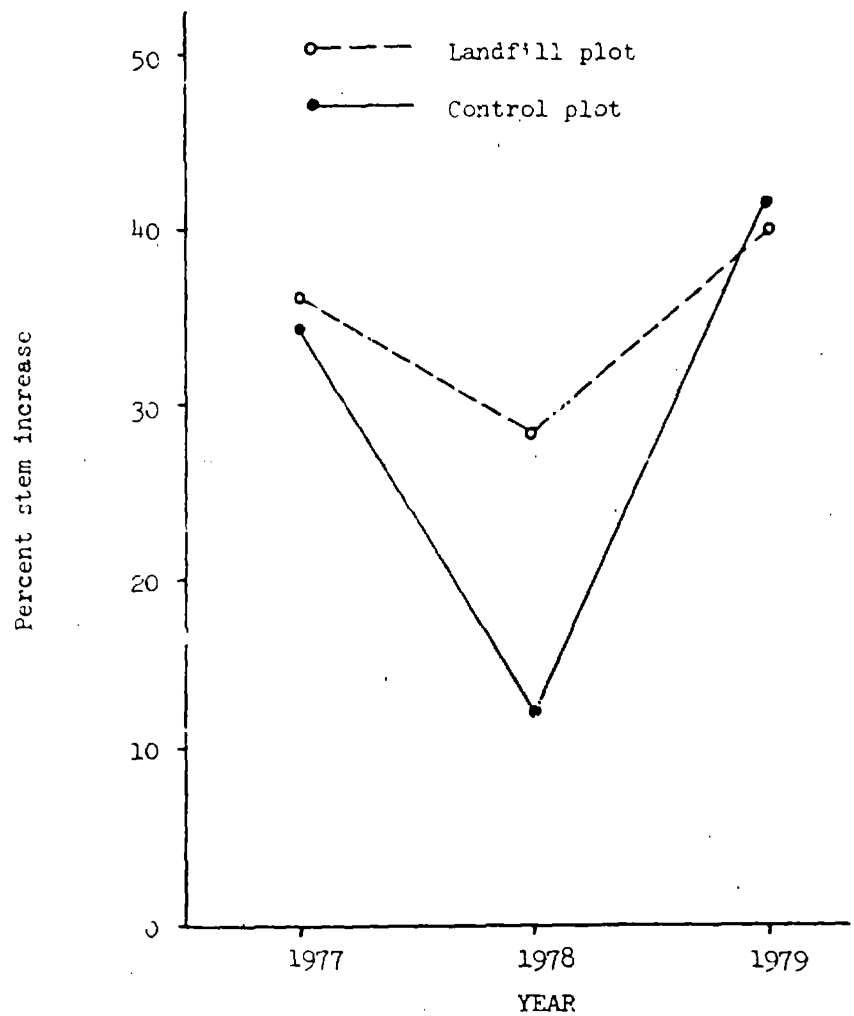

Figure A-14. Norway spruce percent stem increase during the years 1977 through 1979.

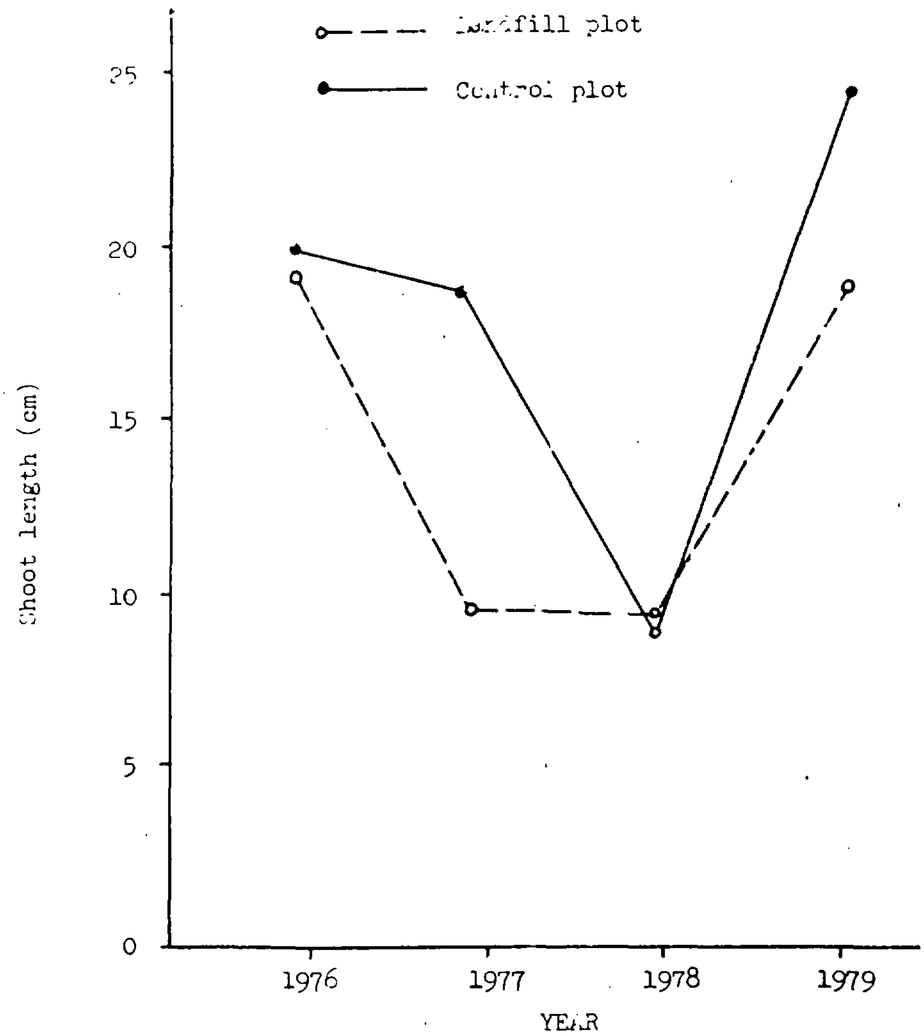

Figure A-15. American basswood shoot length on landfill and control plots from 1976 through 1979.

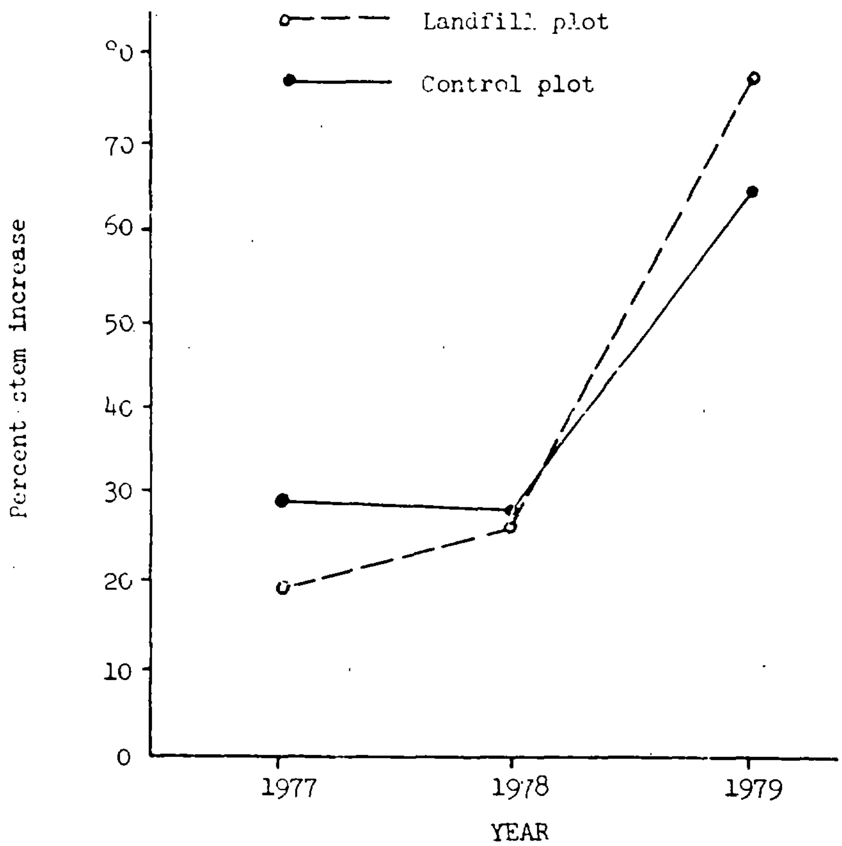

Figure A-16. American basswood percent stem increase during the years 1977 through 1979.

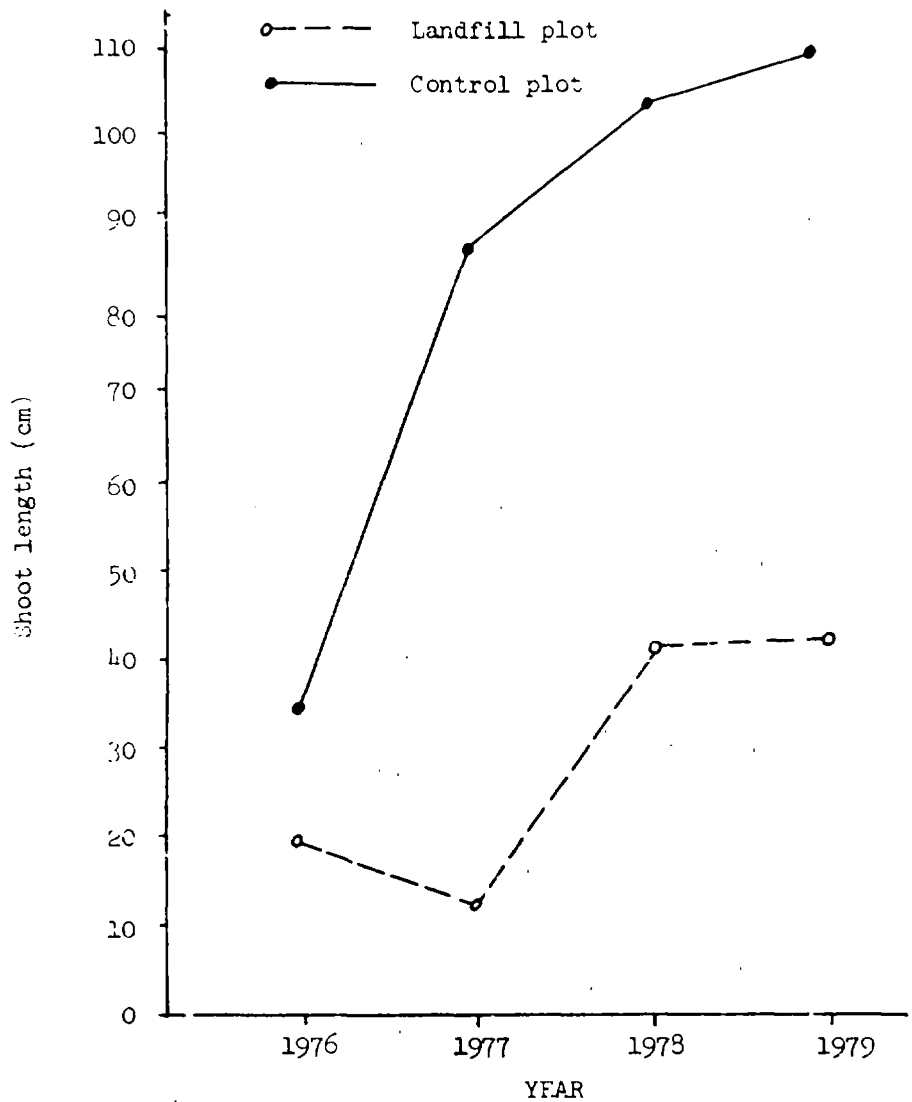

Figure A-17. Hybrid poplar shoot length on landfill and control plots from 1976 through 1979.

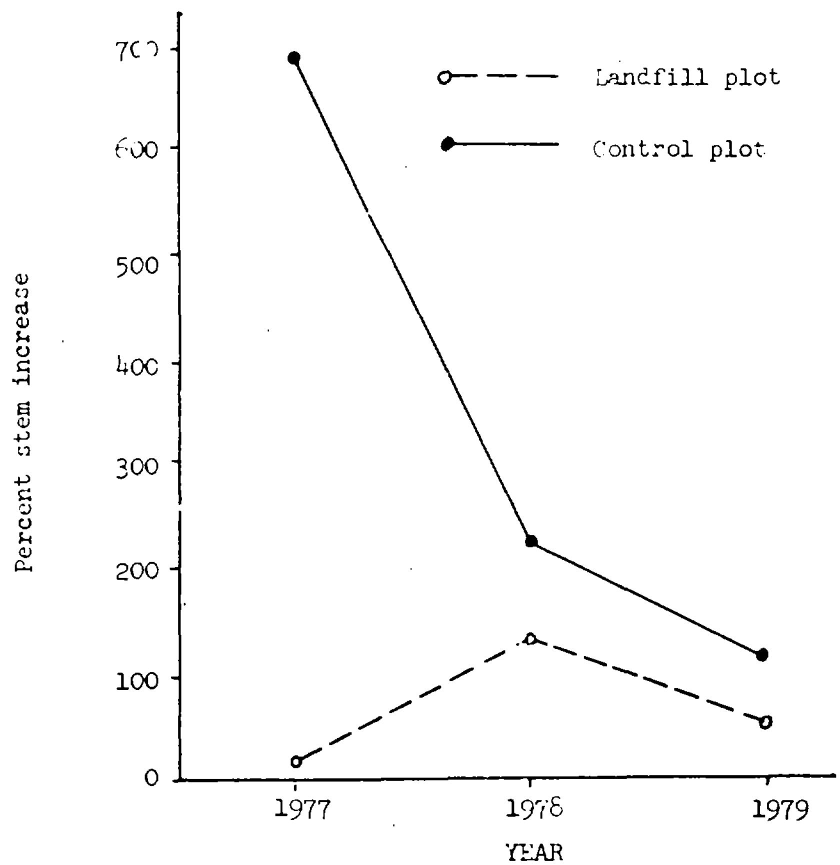

Figure A-18. Hybrid poplar percent stem increase during the years 1977 through 1979.

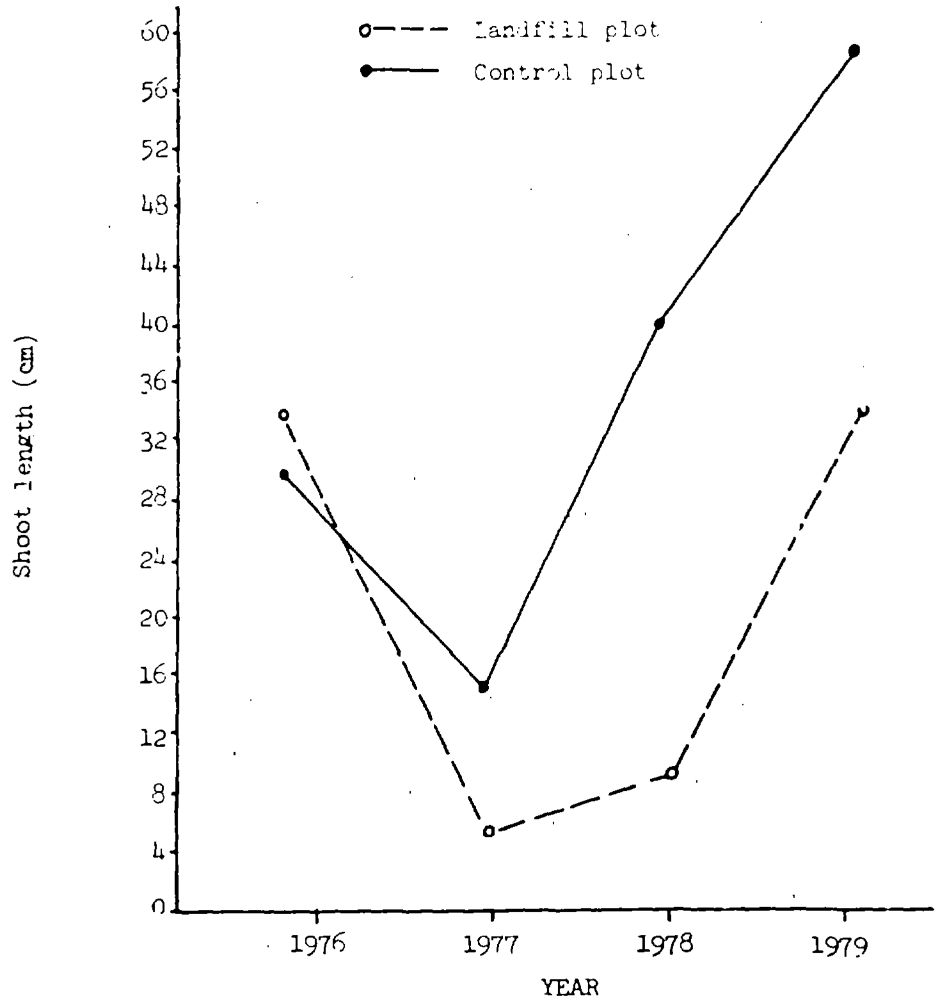

Figure A-19. Green ash shoot length on landfill and control plot from 1976 through 1979.

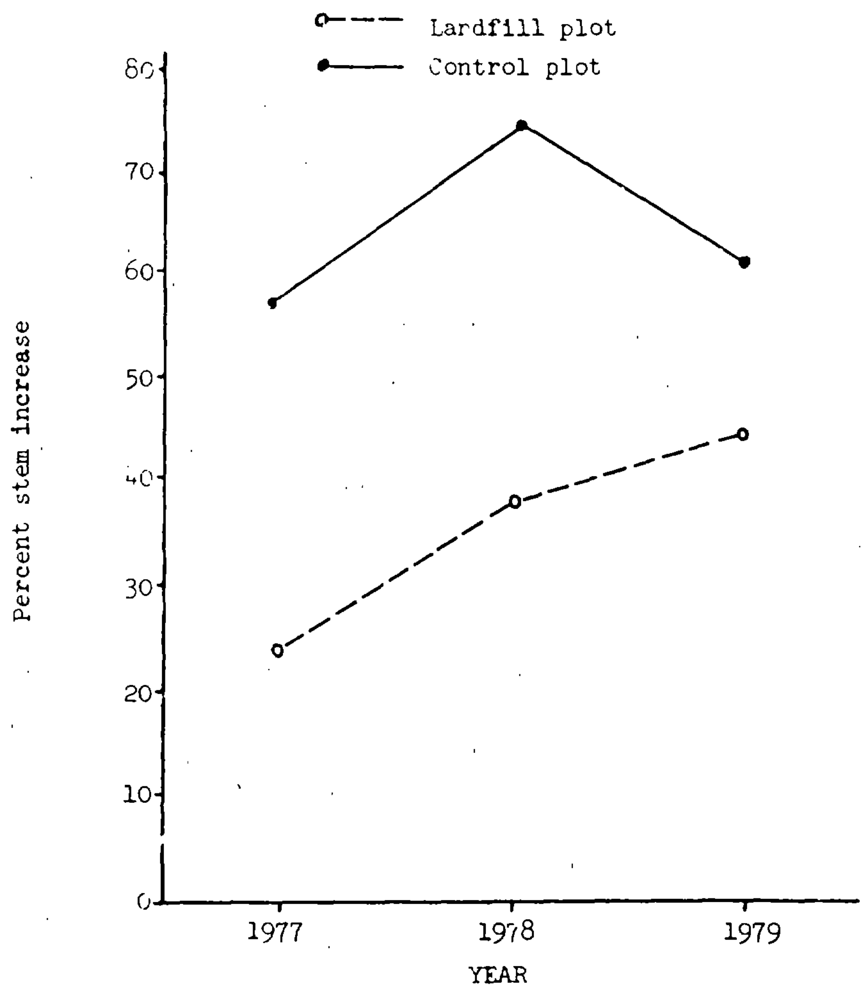

Figure A-20. Green ash percent stem increase during the years 1977 through 1979.

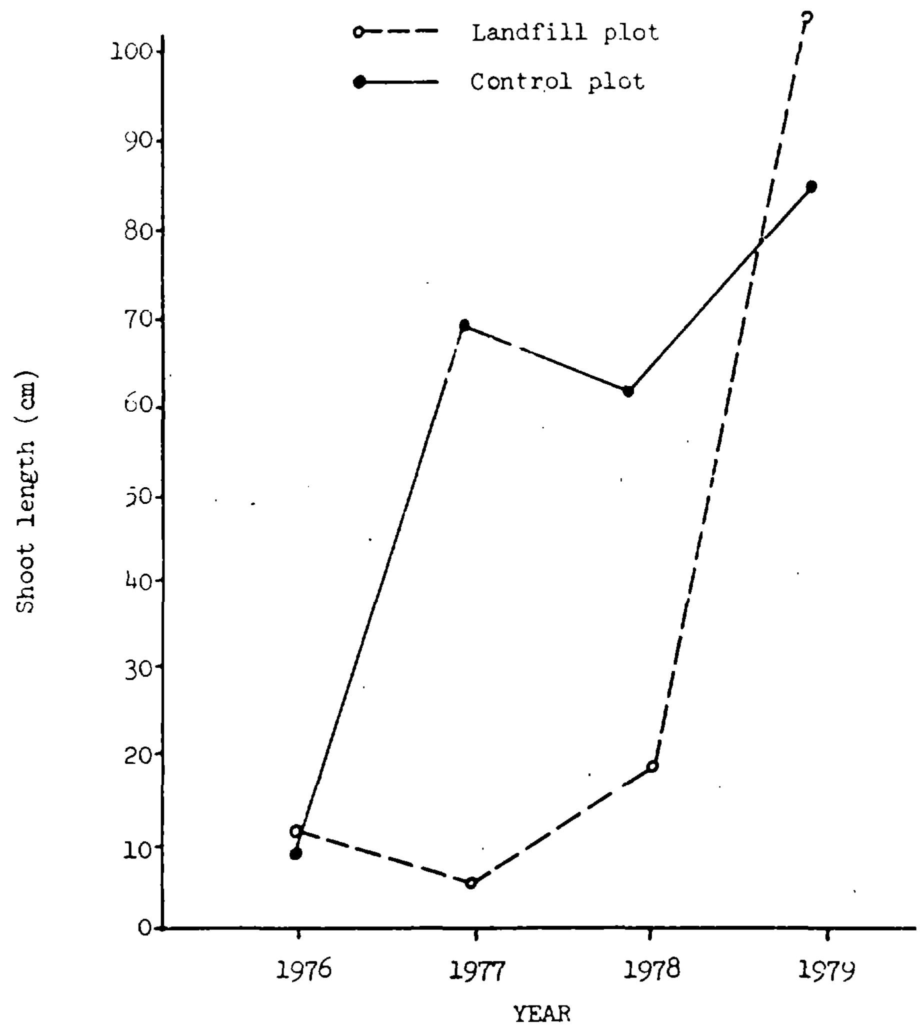

Figure A-21. Honey locust shoot length during the years 1977 through 1979.

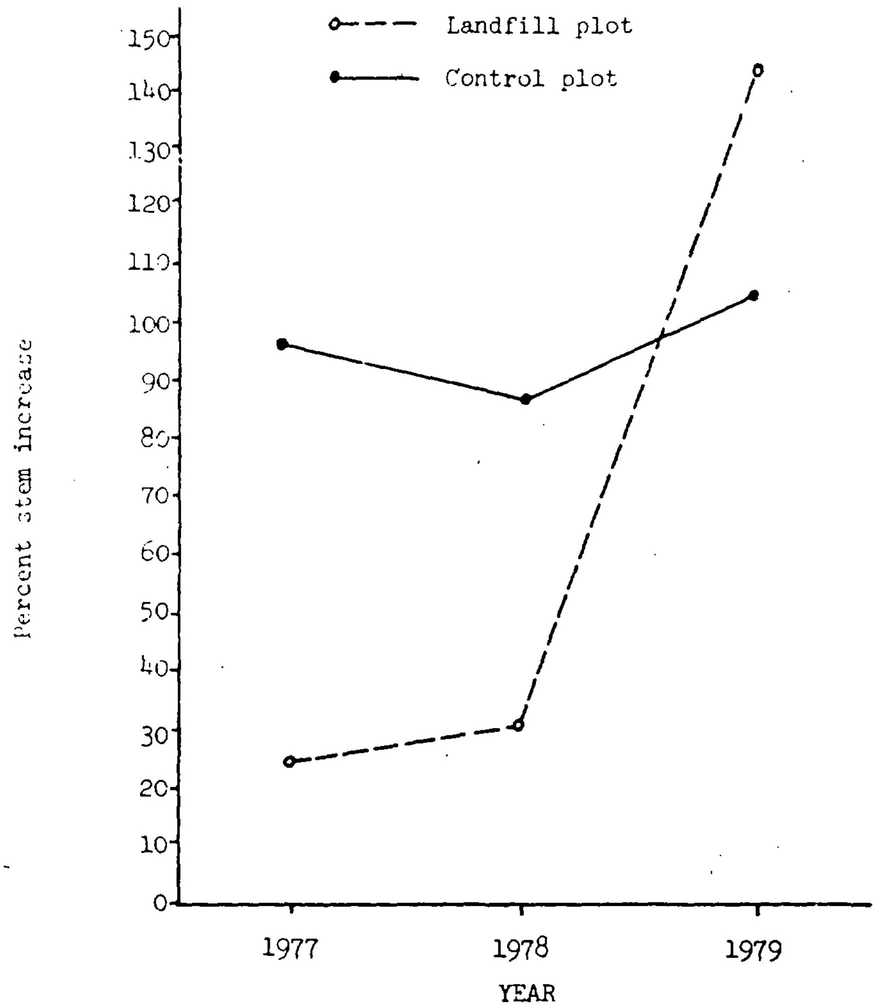

Figure A-22. Honey locust percent stem increase during the years 1977 through 1979.

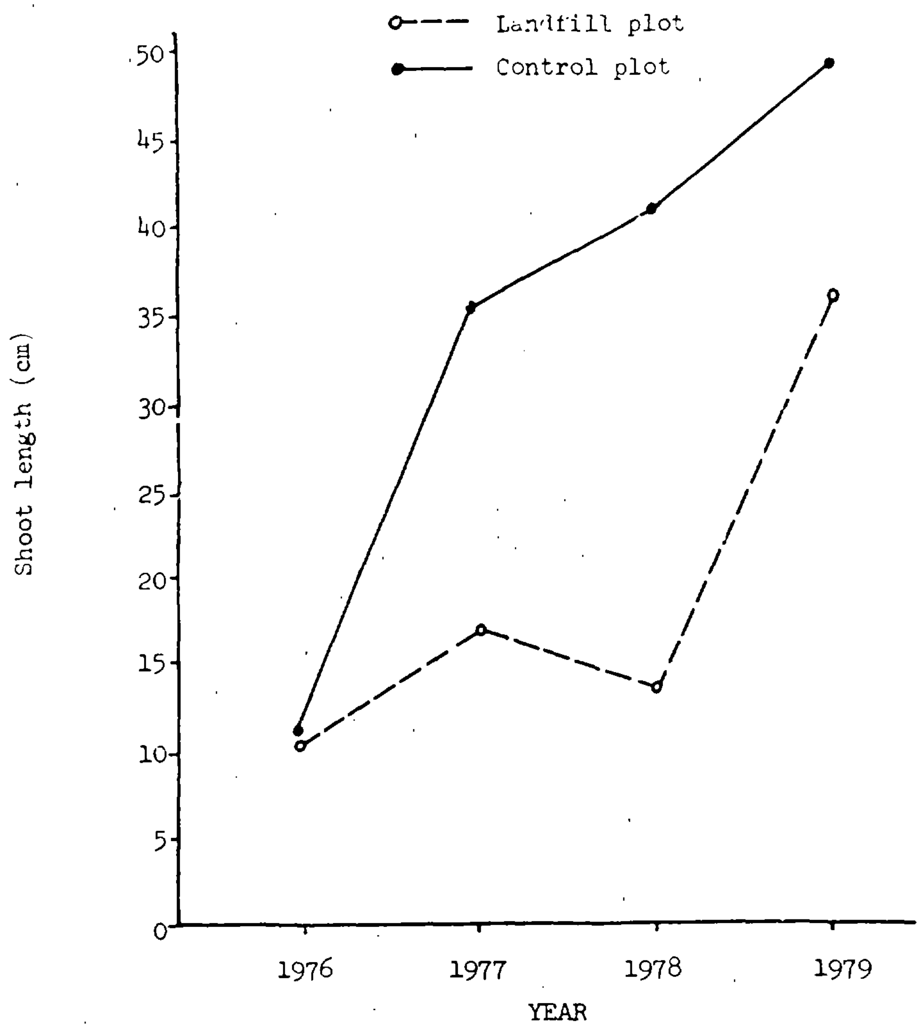

Figure A-23. Sweet gum shoot length on landfill and control plots from 1976 through 1979.

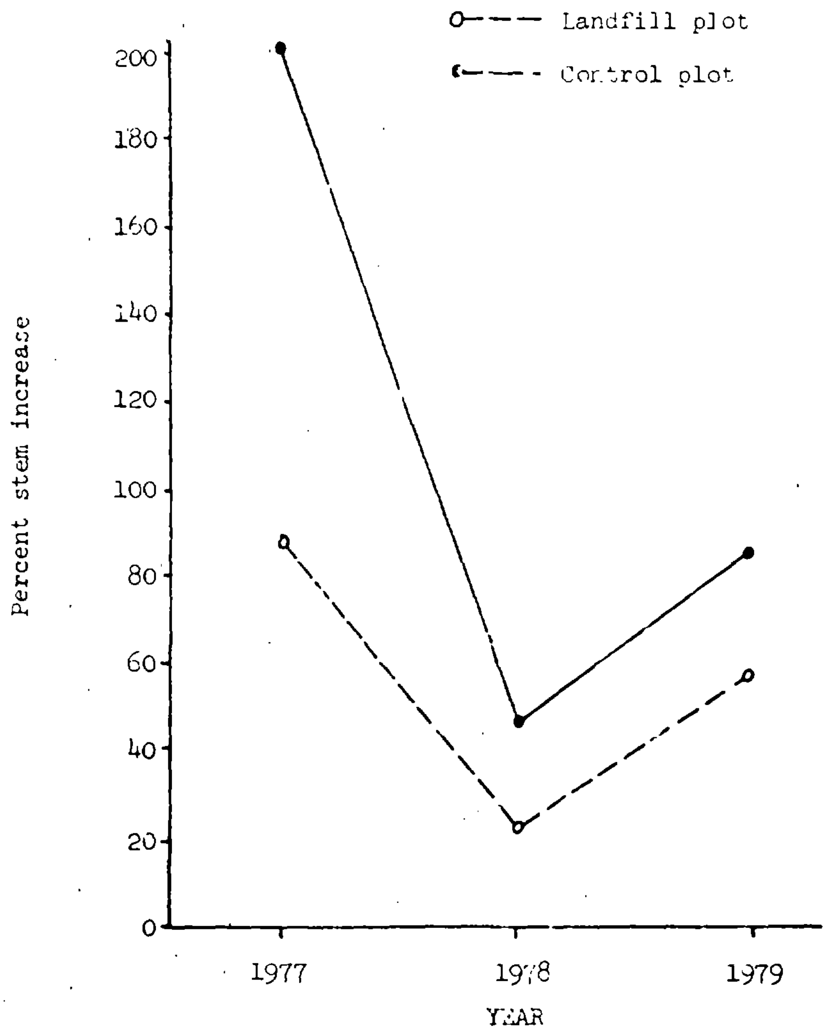

Figure A-24. Sweet gum percent stem increase during the years 1977 through 1979.

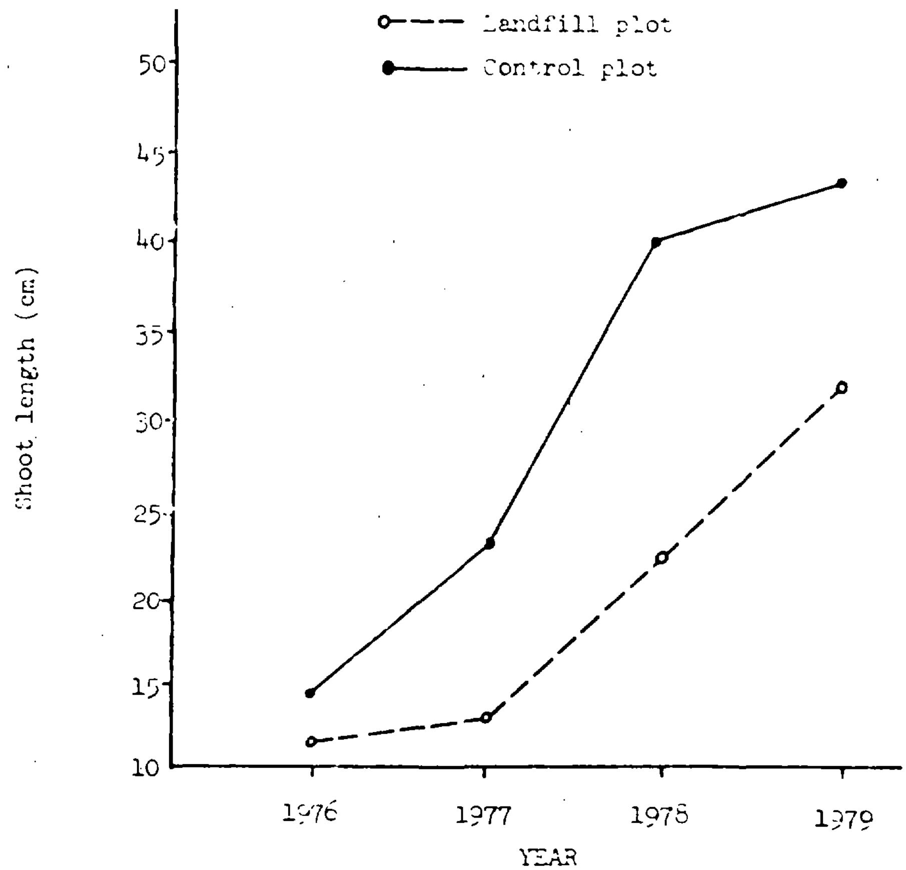

Figure A-25. Pin oak shoot length or landfill and control plots from 1976 through 1979.

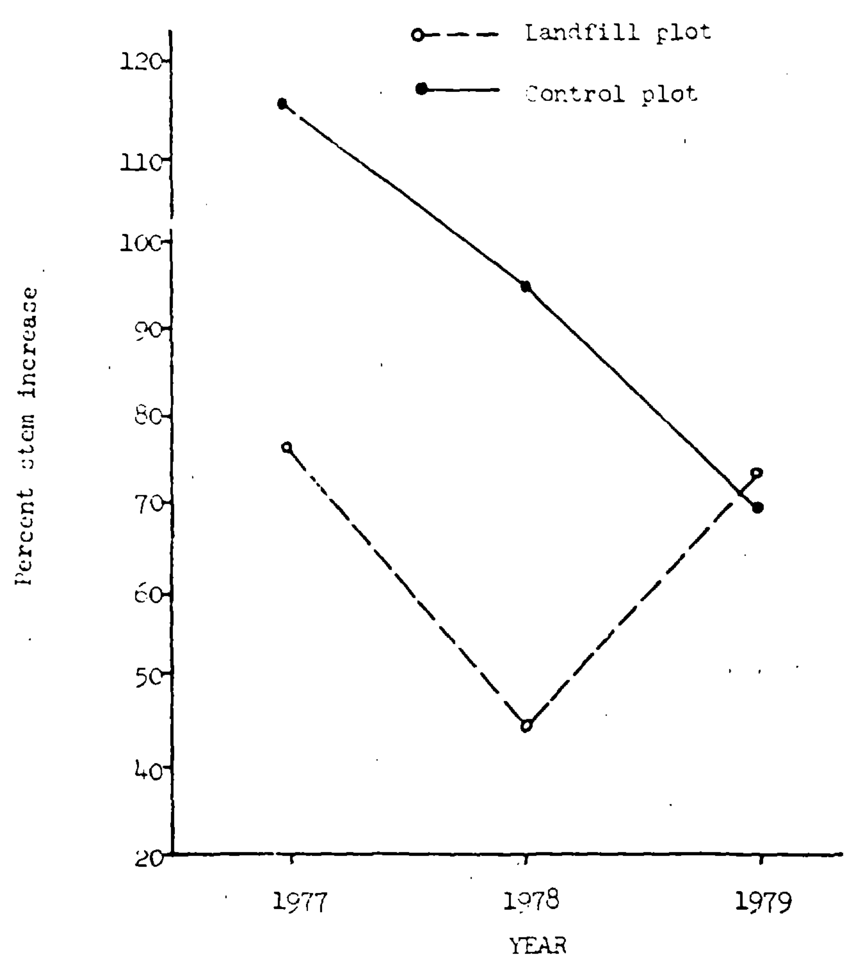

Figure A-26. Pin oak percent stem increase during the years 1977 through 1979.

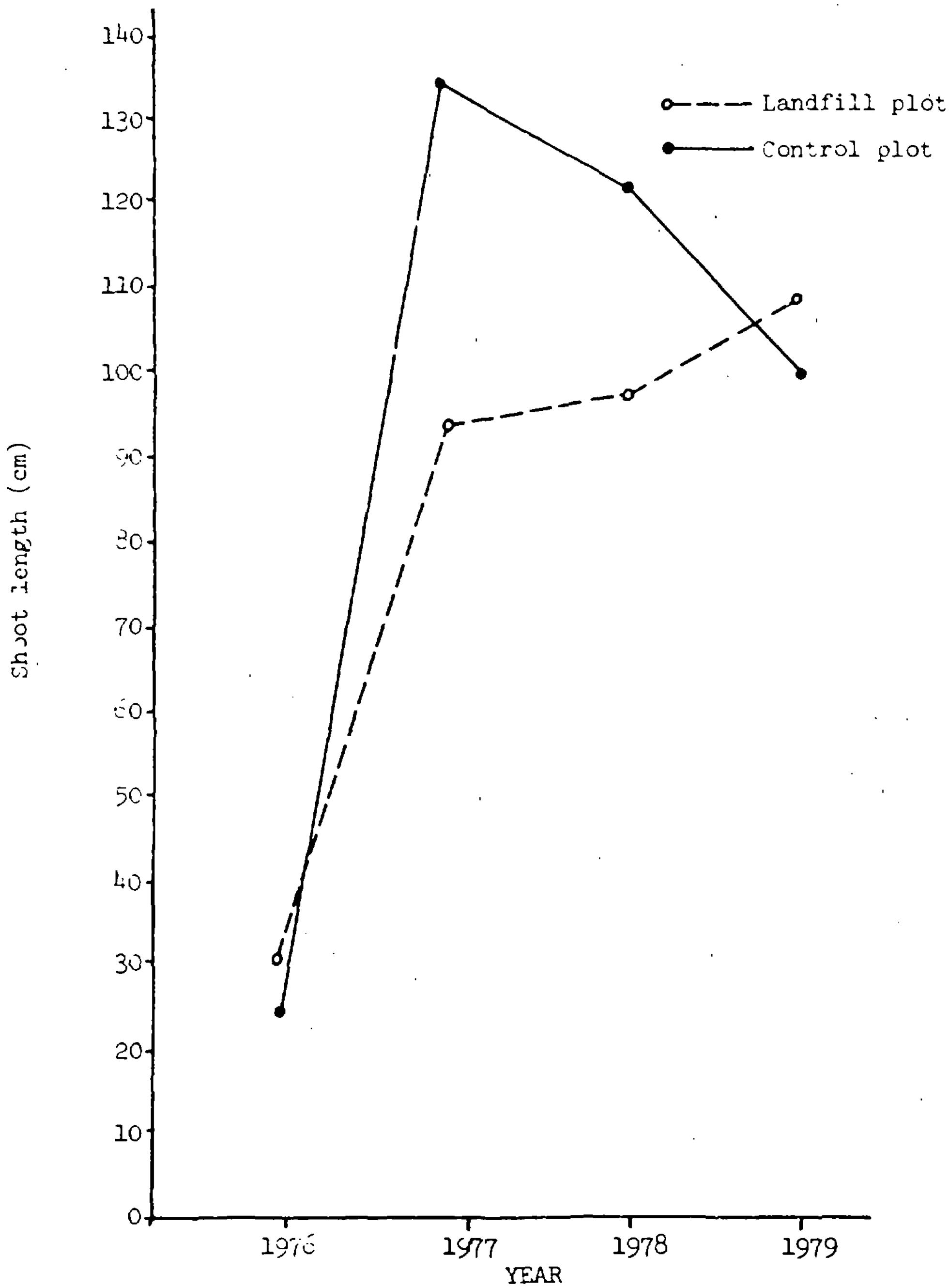

Figure A-27. Hybrid poplar rooted cuttings shoot length on landfill and control plots from 1976 through 1979.

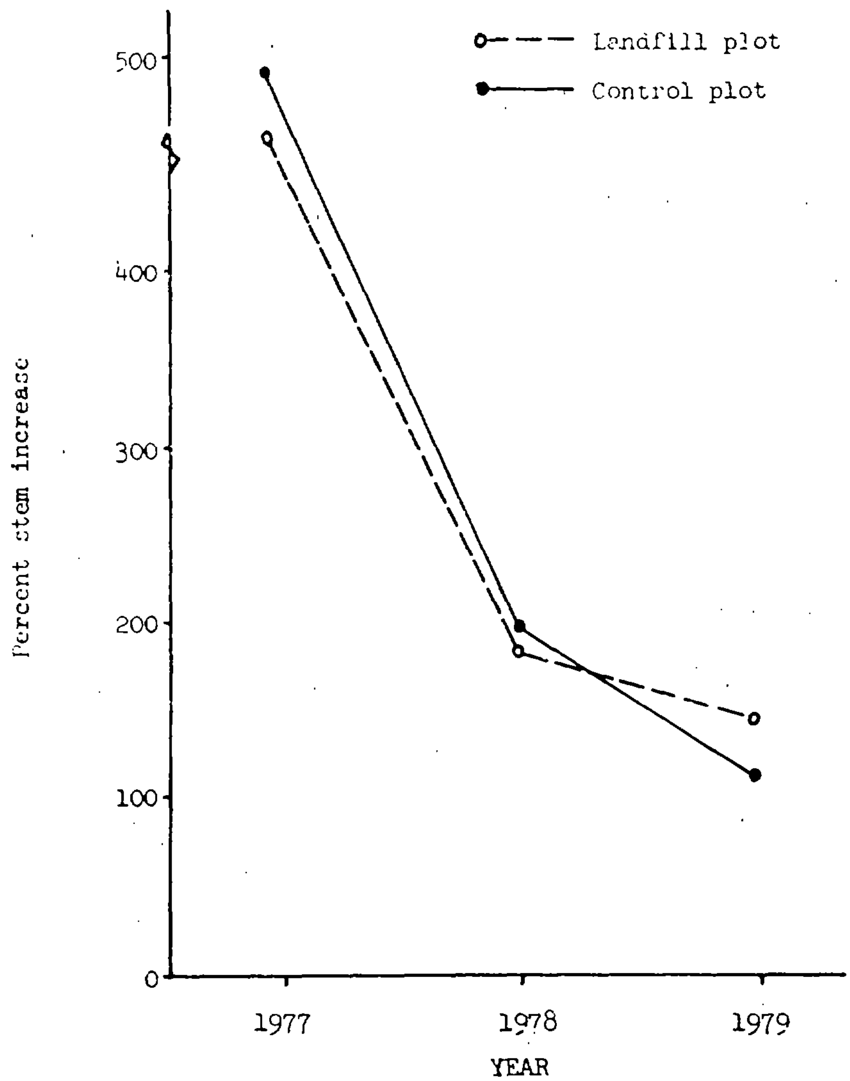

Figure A-28. Hybrid poplar rooted cuttings percent stem increase during the years 1977 through 1979.

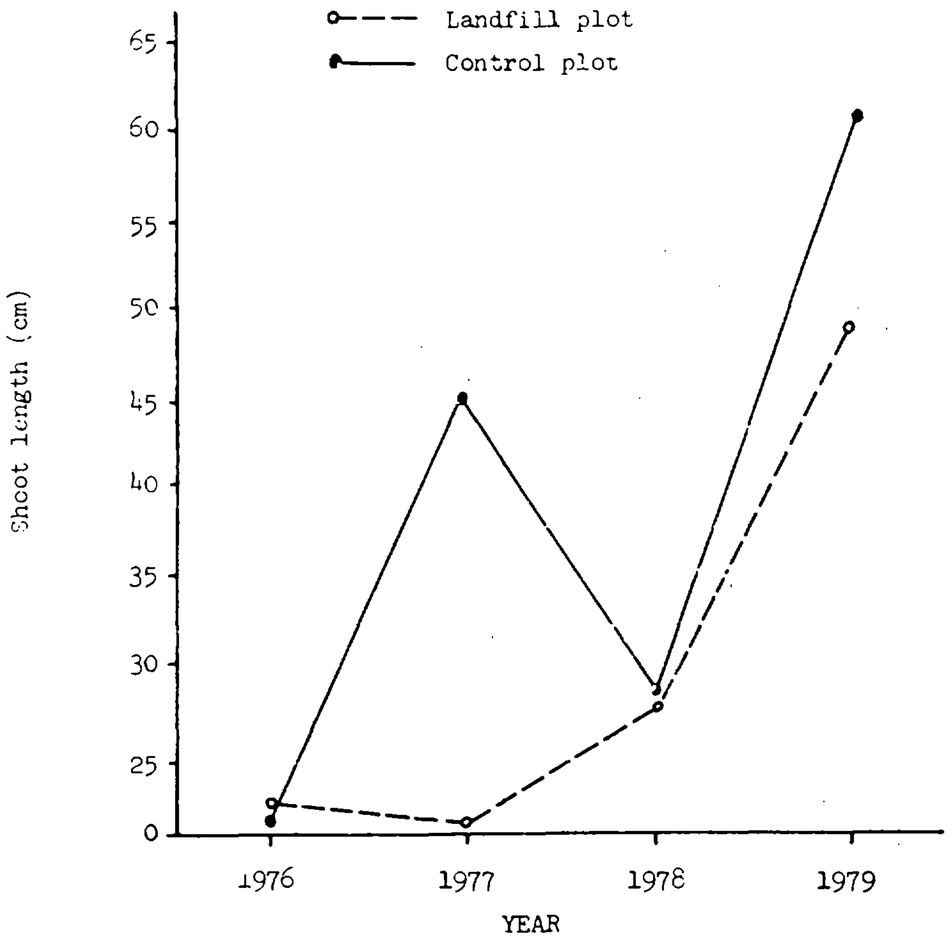

Figure A-29. Red maple shoot length on landfill and control plots from 1976 through 1979.

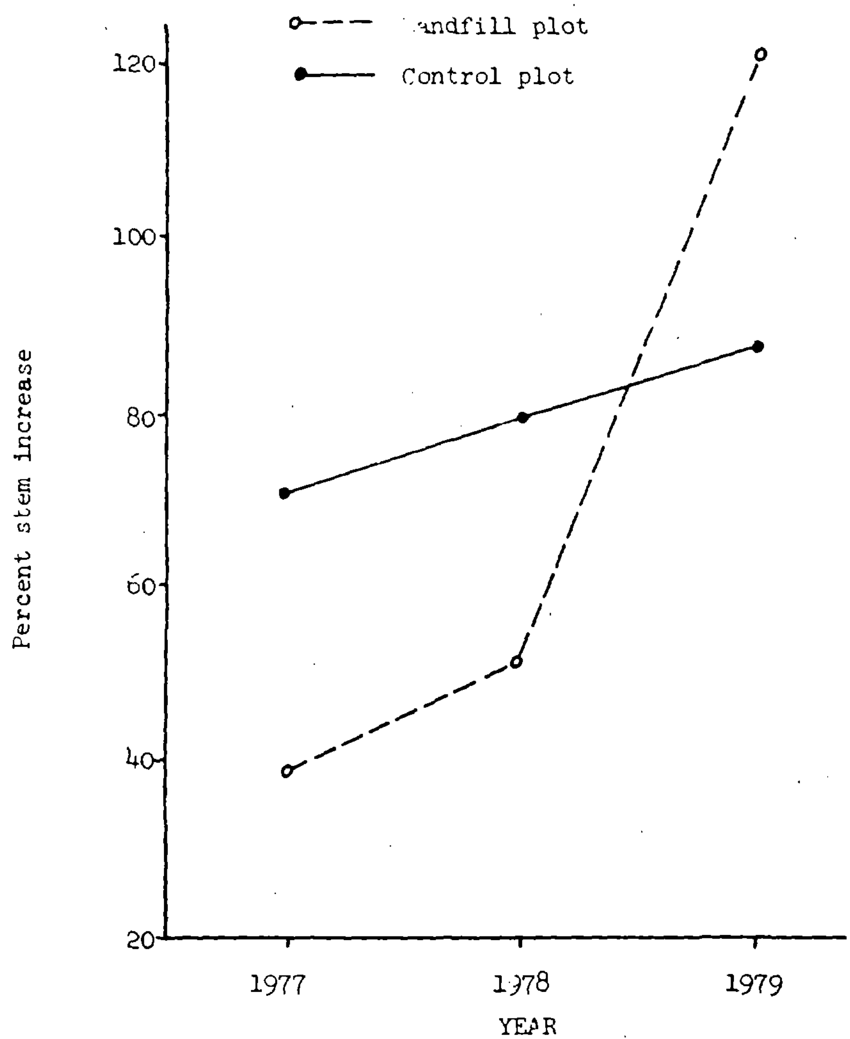

Figure A-30. Red maple percent stem increase during the years 1977 through 1979.

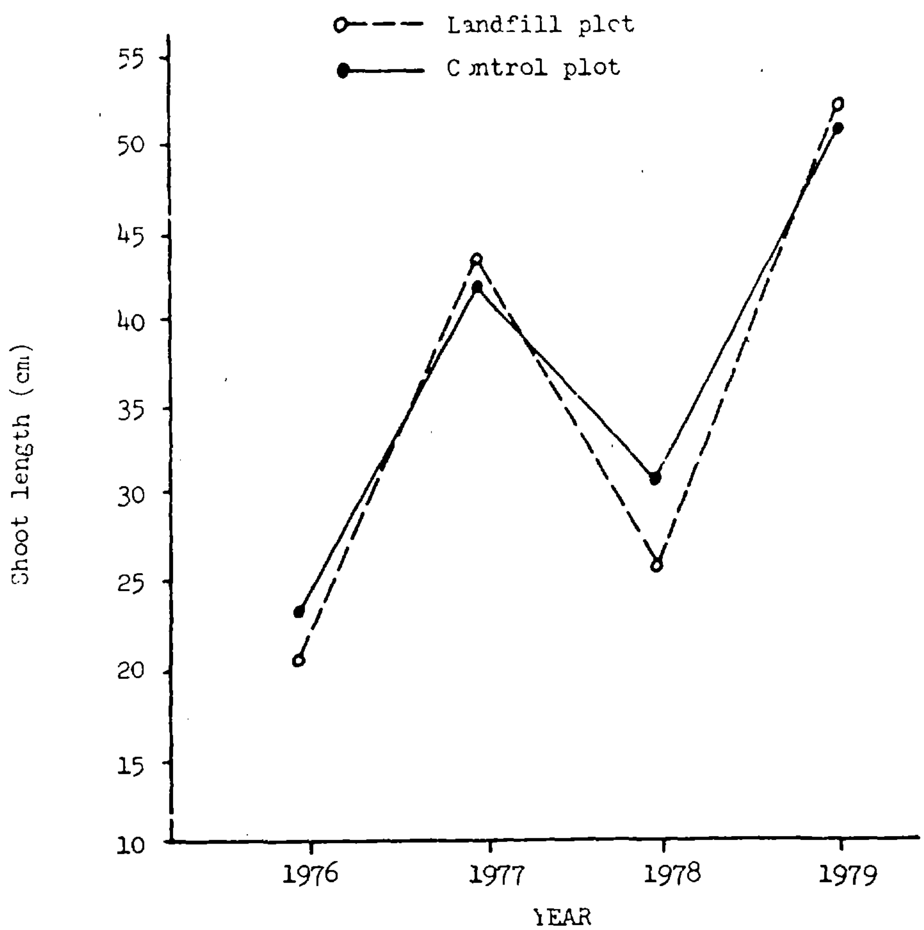

Figure A-31. American sycamore shoot length on landfill and control plots from 1976 through 1979.

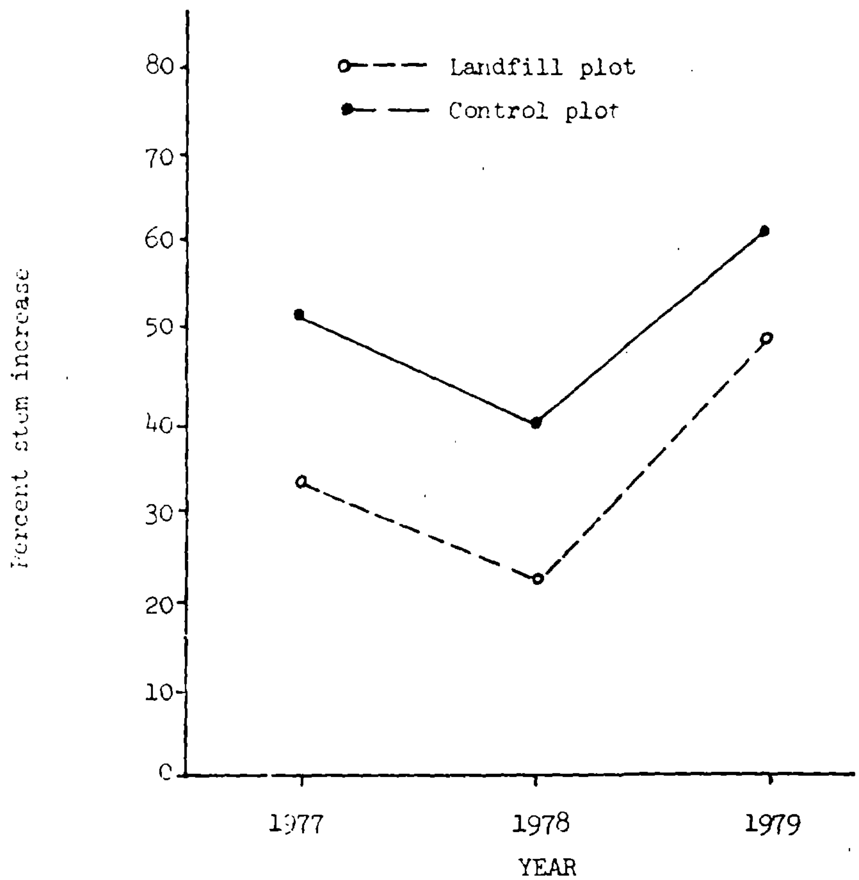

Figure A-32. American sycamore percent stem increase during the years 1977 through 1979.

APPENDIX B

CORRELATION COEFFICIENTS (r) OF SOIL PARAMETERS WITH FOUR GROWTH MEASUREMENTS

	Shoot length	Leaf weight	Root biomass	Stem area increase
O_2	+0.50*	+0.37*	+0.33*	+0.48*
CO_2	-0.55*	-0.41*	-0.37*	-0.51*
K (Oct.)	+0.43*	+0.43*	+0.33*	+0.50*
Mn (June)	+0.53*	+0.48*	+0.23*	+0.61*
Diff. in Mn (June - Oct.)	+0.65*	+0.59*	+0.27	+0.73*
NO_3 (Oct.)	+0.60*	+0.64*	+0.58*	+0.54*
Moisture content	+0.02	+0.03	+0.37*	+0.08
Bulk density	+0.59*	+0.64*	+0.58*	+0.54*

*Significant @ P<.05.

APPENDIX C

SIGNIFICANT SOIL PARAMETERS IN THE REGRESSION EQUATIONS FOR DETERMINATION OF BASSWOOD NUTRIENT CONCENTRATION

Nutrient	B_0	B_1	B_2	R_2	P level
		Regression parameters			
Manganese	-0.1	+0.3 oxygen		67%	<.01
Iron	-2.5	+0.1 highest temperature		57%	<.02
Potassium	2.0	+0.05 oxygen		36%	<.08
Magnesium	1.2	+0.01 oxygen		36%	<.08
Calcium	7.8	-0.07 highest temperature		78%	<.01
Zinc		No significant effects			<.10
Copper	0.3	+0.003 highest temperature		48%	<.04
Nitrogen	3.2	+0.05 oxygen	-0.006 bulk density	84%	<.05

Legend: B_0 = Y intercept, B_1 = Regression Coefficient, B_2 = Regression Coefficient, R_2 = Coefficient of Determination.

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Restoration of Woody Plants to Capped Landfills: Root Dynamics in an Engineered Soil

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Abstract

Closed or abandoned landfills represent significant land areas, often in or near urban centers, that are potential sites for ecological restoration of native woodlands. But current guidelines in many jurisdictions do not allow for the installation of trees or shrubs above landfill clay caps, although these plants have many environmental, functional, and aesthetic advantages, including a rapid start to community succession. Typical closure procedures for capped landfills include only a grass cover to control moisture infiltration and impede soil erosion. The main concern that limits the application of a woody cover to a closed landfill is that roots may penetrate and weaken the clay cap. As part of a comprehensive experimental program on woodland restoration, we installed 22 tree and shrub species on Staten Island, New York (the Fresh Kills Sanitary Landfill). We found no evidence that roots of the transplanted woody plants penetrate caps used on these landfills. Root growth requirements and dynamics stop penetration of these materials. Anoxic and acidic conditions were found in the sandy soil above the cap, as indicated by corrosion patterns on steel test rods. Also, the intensity of mycorrhizal infection on the experimental plants was high in the surface soil and decreased progressively with increasing soil depth. The potential vertical rooting depth during this time period was greater than that occurring over the clay cap. This was shown from data collected on a nearby control site, where seven of the species were installed on an engineered soil lacking a clay barrier layer, and roots of all seven species penetrated deeper than on the landfill. The engineered landfill soils are poor growth media for roots, and below ground constraints that limit restoration on these sites must be addressed.

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Introduction

Land rehabilitation can include restoring diverse plant communities to damaged or derelict land. In urban settings, landfills represent large areas that potentially could become public amenities and wildlife habitat if forest restorations were possible. Protocols to accomplish these goals must be developed, including procedures that acknowledge the many environmental concerns that landfill managers must address. Many landfills are capped with clay to retard water infiltration. Also, material placed over the cap (often a stockpiled mineral soil) is typically low in organic matter and lacks a rich soil fauna and microflora (Dobson & Moffat 1993, 1995).

Concern has been voiced by regulatory authorities that woody plant roots might damage landfill capping materials. In a previous paper, however, Robinson and Handel (1995) described the results of woody plant excavations conducted on a closed-capped municipal landfill. Vertical root growth of 13 species that had invaded naturally from nearby forests was completely constrained by a 45-cm compacted clay cap that was covered with a thin topsoil layer (≤30 cm). These plants had extremely shallow root plates, which remained above and parallel to the clay barrier. These earlier results provided a rigorous test of the hypothesis that woody plants would not pose a hazard to landfill clay caps. But no controls (i.e., plants growing off the cap) were examined, and only a limited number of species could be studied. Some species have the capacity to develop deeper root systems than others, but clay caps may be a difficult barrier for any woody plant roots to penetrate. These issues are important in the design and planning of restored sites, particularly those on shallow, engineered soils.

Three factors must be considered regarding the use of woody plant species over clay-capped landfills. First, can roots breach a standard clay barrier? Second, will "opportunistic" roots take advantage of subsidence cracks or other breaks in the clay barrier, penetrate through them, and create further damage? Third, will the soil and subsoil cover materials encourage downward growth of the roots of woody plant species towards the clay cap so that the first two concerns become reality?

Earlier research (Robinson & Handel 1995) addressed the first two concerns. Our research addresses the role of soil and subsoil in the root-system development. Four questions are addressed in this study: (1) What are the root growth patterns of woody plants grown above a clay cap? (2) Do the root growth patterns differ from those produced by the same species grown in a site that lacks capping clay? (3) When the roots come into contact with capping clay, do they penetrate through the clay? (4) How does proximity of root systems to the clay cap affect mycorrhizal infection potential? The fourth question is of wide interest because little is known about the performance of mycorrhizae in reconstructed soil profiles, except in rehabilitated mined lands (Miller 1987; Miller & Jastrow 1992).

Methods

Study Site

The Fresh Kills Sanitary Landfill is located on the western shore of Staten Island, New York. The landfill complex, which is operated by the New York City Department of Sanitation (NYC-DOS), covers almost 1300 ha and is one of the largest such facilities ever constructed. About 11–13 Mg (12,000–14,000 tons) of municipal waste from the five boroughs of New York City are deposited daily into the Fresh Kills landfill. There is interest in recreating native upland woodlands on the closed portion of the landfill to enhance the natural resources of Staten Island that have been depleted by past development (Robinson et al. 1994).

The portion of the Fresh Kills complex where our experiments were conducted, Section 2/8, was closed in 1991 and hereafter is referred to as the "landfill" site. The garbage was encased in a clay layer 45 cm thick, which was graded and compacted under NYC-DOS specifications to produce a barrier with very low hydraulic conductivity ($K_s = 10^{-7}$ cm sec^{-1}). The clay cap was covered, in turn, with 60 cm of subsoil material (the barrier protection layer) and finally with 15 cm of residential fill. The surface soil materials were specified to have a sandy loam texture, free of construction debris and other materials larger than 76 mm in diameter, and to have a pH of 4.5–6.0. The final cover was sown with a mix of nonnative grasses and legumes, which formed a dense cover at the time of planting the trees and shrubs.

To study root dynamics on this site, 17 species of native trees and shrubs were selected for planting (see Table 1), based on their suitability for growth on Staten Island. They also spanned a range of tolerance to

Table 1. Vertical root depth (cm) of trees and shrubs excavated in 1992 and 1993 on the Fresh Kills Landfill (section 2/8).*

Plant Type	*Species*	*1992*	n	*1993*	n
Planted Trees	*Acer rubrum*	27 (20–35)	4	38 (26–48)	5
	Fraxinus pennsylvanica	29 (18–40)	4	33 (20–41)	4
	Juniperus virginiana	21 (14–30)	4	35 (27–43)	5
	Pinus rigida	21 (18–24)	2	33 (26–41)	4
	Pinus strobus	25 (15–38)	6	34 (30–37)	5
	Platanus occidentalis	35 (14–55)	5	42 (33–64)	6
	Prunus serotina	17 (12–22)	3		
	Quercus palustris	26 (17–34)	4	52 (31–69)	3
	Quercus prinus	16	2	29	1
Planted Shrubs	*Amelanchier canadensis*	21 (8–29)	3	27	1
	Cornus amomum	21 (10–34)	9	32	1
	Cornus racemosa	42 (27–57)	2		
	Myrica pensylvanica	20 (16–24)	4	27 (20–34)	2
	Prunus maritima	18 (12–22)	4		
	Sambucus canadensis	15	1		
	Vaccinium corymbosum	22 (17–27)	2		
	Viburnum dentatum	24 (14–30)	3		
Volunteer Trees	*Populus tremuloides*	34 (12–52)	3	40 (36–43)	2
	Robinia pseudoacacia	32	1	29 (20–34)	3
Volunteer Shrubs	*Baccharis halimifolia*	37	1		
	Rhus copallina			47	1
	Salix discolor	26	1		

*Means (ranges) are reported for each year.

potential variation in soil moisture along a slope, as well as a range of potential rooting depths and root morphologies. Woody species were purchased from area nurseries and planted by a contractor in the spring of 1992 by means of standard horticultural techniques, except that all soil was removed from root balls before planting. Trees were 1.5–2.0 m tall, and shrubs were 60–100 cm tall. About 550 plants were installed at 5-m intervals in a 15-row grid across the south face of Section 2/8. The 15 rows of the grid covered most of the slope (Fig. 1), with each species represented two to three times in each row (30+ individuals per species). The grass cover was mowed between the woody plants, but no irrigation or fertilizer were used on the site, conditions expected under normal landfill cover maintenance.

In 1992, the same species from the same nursery sources were also planted on an earthen berm adjacent to the eastern perimeter of the landfill complex, opposite the Richmond Avenue Mall (hereafter referred to as the "berm" site). The plants were arranged in a four-row grid on the western face of the berm, which was a deep embankment of sandy loam soil amended with composted leaf mulch, but with no clay layer. The ground cover was a thick mat of the vine *Lonicera japonica* (Japanese honeysuckle), which was mowed before planting.

All planting was completed by early June 1992. A few replacements were required, in cases where planting was done improperly or incorrect species were planted. The installation of replacements was completed in July 1992.

Field Excavations

We excavated representative samples (1–9 plants per species) at random points on the grid between October and November 1992 and in November 1993. Fifteen of the 17 planted species were deemed large enough to examine in 1992, while the other two species were too small to be useful in this study, as determined from preliminary test excavations. In 1993 we dug up individuals from 12 species, passing over 5 species deemed too small to have accrued significant root growth. A few additional woody species were found growing on the site as natural recruits from adjacent woodlots. Specimens of these volunteers also were excavated to enrich our data set.

The plants were excavated by hand, or in the case of large trees were trenched by a back hoe on three sides, then undercut and tipped to determine maximum rooting depth. The depth to which roots (especially fine roots less than 5 mm diameter) extended downward from the original root ball was reported as the "vertical rooting depth" (cm), while the depth that fine roots proliferated in the topsoil and subsoil material was reported as the "lateral rooting depth" (cm). Also, we noted variation in the depth of overburden and recorded this in 1993. Roots of each specimen were photographed, after which stem height and girth (15 cm above the ground surface or, in the case of shrubs, stem number) were measured. The plants were then tagged and replanted. No capping clay was removed during these studies, and all soil was replaced. Additional individuals of each species are still in the ground, undisturbed, and are available for future research.

Soil Properties

During the plant excavations, samples were collected from the topsoil (0–10 cm) and subsoil (20–30 cm depth) and in the landfill site from the clay barrier. Each field-moist sample was thoroughly mixed before a subsample was removed for the determination of pH. Soil pH was measured potentiometrically in a slurry (20 mL deionized water: 10 g soil) made with fresh soil (Hendershot et al. 1993). The remaining soil was air-dried and submitted to the Soil Testing Laboratory of Rutgers University for textural analysis. Sand, silt, and clay fractions were determined by the Bouyoucos hydrometer method (Sheldrick & Wang 1993).

Aeration status of the bulk soil was determined by periodically extracting mild steel rods (6 mm diameter × 750 mm), which had been inserted into the soil profile, and examining them for signs of rusting (Carnell & Anderson 1986; Hodge et al. 1993). During late spring, rods were driven vertically into the final cover material of Section 2/8 in five transects down the slope, with 15-m spacing across the slope between the individual rods in each course (for a total of 25 rods). Twenty rods were similarly installed (along four transects) down the slope of the Richmond Avenue berm. Rods were left in place until the late summer or early autumn, when they were removed from the soil profile. Surface patterns of corrosion along the length of each rod were scored, in 5-cm

Figure 1. Experimental plantings of 17 species of native trees and shrubs on the closed and capped Fresh Kill Sanitary Landfill (Section 2/8), Staten Island, New York.

increments, according to the criteria of Carnell and Anderson (1986). The rods were cleaned with steel wool prior to reinstallation in the soil (at a distance of ≥ 20 cm from the point of initial removal). Rods were removed again in late autumn or early winter. Removal and reinstallation of the rods was repeated over two consecutive years.

Mycorrhizal Assessments

In conjunction with the root penetration study, 55 random samples of fine roots were collected from the outer edges of the exposed root systems of trees and shrubs excavated from the landfill and berm sites. The samples were stratified by depth and originated from three positions: (1) near the ground surface, in the topsoil material (hereafter referred to as the top samples); (2) deeper within the soil profile, along the sides of the root ball (side samples); and (3) beneath the main mass of the roots, but above the clay cap, where the greatest downward extent of the root system could be discerned (bottom samples). The root samples were frozen (−20°C) in resealable polyethylene bags until they could be examined in the laboratory. The thawed roots were gently washed free of soil particles over a 1-mm mesh screen, immersed in water, and examined under a dissecting stereoscope for the presence of active and inactive ectomycorrhizal (ECM) fungal infection, according to the criteria of Harvey et al. (1976). Roots then were cut into 2-cm segments, which were cleared in hot (90°C), aqueous KOH (2.5%) and stained with 0.05% trypan blue in glycerol-lactic acid solution (Koske & Gemma 1989). Wet mounts of roots were scored (at 400×) for the presence of endomycorrhizal (VAM) infection.

Results

Soil Properties

Soil properties differed in several respects between the soils over the capping clay and the nearby off-cap control site (Table 1). Although the surface horizon had higher sand content and lower clay content than the subsurface horizon within each profile, there also were marked textural differences between the landfill cover and berm soil profiles. The cover material of the landfill site had a coarser texture than soil sampled from the berm, regardless of horizon (multivariate test of site, Wilks' lambda: $\Lambda = 0.035$, $p < 0.0001$, $F = 539.05$, $df = 2{,}39$). With their much lower sand contents, the two berm soil horizons could be classified as sandy clay loams and clay loams, respectively (Table 1). The surface horizon of the cover material had a loamy sand texture, rather than the sandy loam required by NYC-DOS. Also, contrary to engineering specifications, the mean clay content of the surface horizon was significantly lower than that of the underlying barrier protection layer (Table 1). Furthermore, differences in pH between surface soil and subsoil horizons were more pronounced in the landfill cover than in the berm soil. Surface horizon pH in both sites was circumneutral, but the subsurface layer on the landfill site was very acidic, more closely resembling the conditions found in the clay barrier (Table 1).

The average depth (±SE) to which the soil remained aerobic was greater in the berm soil (46.2 ± 6.0 cm) than in the landfill soil (22.8 ± 1.9 cm). This site difference was determined from oxidized portions of the rods installed in the two locations and was highly significant (two-sample t test: $t = 4.89$, $p < 0.0001$, $df = 57$). In the surface layers of the soil, these rods were heavily coated with orange-to-red rust patches, which were indicative of well-aerated soil conditions, according to the criteria of Carnell and Anderson (1986). Below the zone of pronounced rusting, rods typically exhibited a matte gray or smooth black finish, which indicated sustained anoxia (Carnell and Anderson 1986).

Significant spatial variation also was observed for the steel rods incubated within the landfill site. On the landfill site (Fig. 2), the depth to which rods were highly rusted decreased significantly and progressively from the crest (31.22 ± 3.92 cm) to the toe (14.33 ± 2.86 cm) of the slope (F test, main effect of slope: $p < 0.0001$, $F = 9.74$, $df = 4{,}26$). The most comprehensive set of readings that documented the corrosion patterns of the installed steel rods was taken in the late summer of 1992 from the landfill cover and the berm. Data collected on subsequent dates were more fragmentary, owing to the loss of rods during mowing operations or excavations conducted on the slope. The depth to which the soil remained aerobic varied temporally (F test, slope by time interaction: $p = 0.045$, $F = 2.38$, $df = 8{,}26$), but measurements within each sampling period generally mirrored the trend depicted in Fig. 2.

Field Excavations

The results of the Section 2/8 excavations are summarized in Table 2. In 1992 none of the planted individuals had grown roots deep enough to encounter the clay cap, although several species had relatively deep roots. Because this group of plants included fairly substantial trees (375–400 cm in height) and many of the specimens were planted as bare-root stock, these results indicated that, at the very least, young or small woody plants are not likely to represent a danger to the cap. The few volunteer plants that we examined originated from seed one year earlier, but they did not have deep roots either; however, our sample size was small.

In 1993, vertical root growth increased for the majority of species that had been measured in 1992 (Wilcoxon signed-rank test: $Z = 2.70$, $p = 0.0069$; Table 2). Maxi-

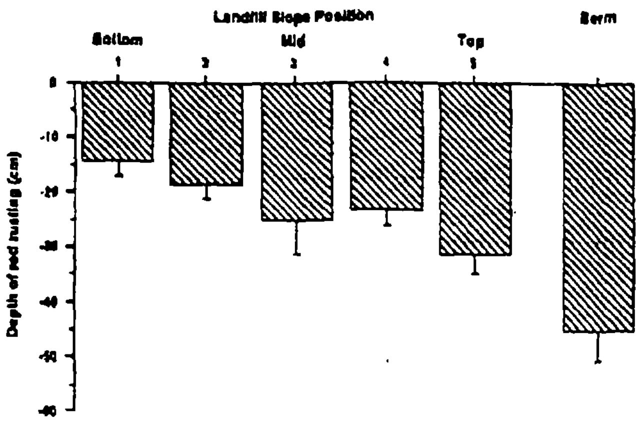

Figure 2. Depth (cm) of rusting of steel rods at different slope positions on the landfill, contrasted with the berm site. For the landfill, means (±SE) represent the averages of 7–9 samples collected from August of 1992 to December of 1994; the site value for the berm is the mean of 19 samples. The depth of rusting indicates the depth of aerobic soil conditions.

mum rooting depth of the experimental plantings increased slightly with depth of soil to the clay cap (F test of regression: $F = 6.29$, $p = 0.017$, $df = 1{,}37$; $r^2 = 0.145$). There was some local variation away from the expected on-site specification of 75 cm (one-sample t test: $t = 4.08$, $p < 0.01$). Depth to the cap varied from 30 to 100 cm, but all root systems were still well above the clay layer (Fig. 3).

Vertical positioning of plants on the slope also had several effects on root performance, although absolute rooting depth did not vary directly as a function of distance from the slope base (F test of regression: $p = 0.73$). First, overburden depth increased slightly from the bottom to the top of the landfill site, averaging about 25 cm deeper at the toe, although there was much variation (F test of regression: $F = 12.53$, $p = 0.0011$, $df = 1{,}37$; $r^2 = 0.253$). Second, the percentage depth of the overburden occupied by tree and shrub roots was ~40% at the bottom of the slope, increasing to about 63% at the slope crest. This was a slight but significant difference (F test of regression: $F = 10.84$, $p = 0.0022$, $df = 1{,}37$; $r^2 = 0.227$). Third, the depth to which lateral fine roots proliferated did not differ significantly with slope position or depth to the capping clay (F tests of regression: $p > 0.50$); on average, lateral fine roots occupied the uppermost 22.4 ± 1.9 cm of overburden.

Maximum lateral root depth was not significantly correlated with maximum vertical root depth ($p \leq 0.88$), but the depth of lateral root proliferation was significantly correlated with plant stem diameter ($r = 0.415$, $p = 0.008$) and marginally correlated with plant height ($r = 0.30$, $p = 0.06$). Also, as expected, height and stem diameter were significantly and positively correlated ($r = 0.597$, $p < 0.0001$), but neither of these variables was correlated with vertical rooting depth ($p > 0.30$).

In comparing root growth on the capped site with the noncapped site, vertical rooting depths measured over the cap were significantly less for all of the seven species excavated at each site (Friedman's test, blocking on species: $\chi^2_r = 7.00$, $p < 0.01$, $df = 1$; also see Fig. 4). Also,the rooting depth attained by five of the seven species on the berm was comparable to or greater than the depth of the capping clay beneath the same species on the landfill site (Wilcoxon signed-rank test: $Z = 0.73$, p 0.46; Fig. 4). That is, the potential for root extension during the study period was not achieved over the clay cap.

Mycorrhizal Assessments

There was weak interdependence of location and mycorrhizal type (G test of independence: $G = 5.13$, $p = 0.023$), but mycorrhizal infections in the landfill cover material were more frequent in ECM plant species than VAM plants, which were mostly uninfected (Pairwise contrast: $\chi^2 = 5.80$, $p = 0.016$). The latter result is sur-

Table 2. Physicochemical properties of surface and subsurface horizons measured in 1993, on the capped landfill (Section 2/8) and on the noncapped control site (Richmond Avenue berm).*

Site	*Horizon*	*pH (2:1)*	*Sand (%)*	*Silt (%)*	*Clay (%)*	*Textural Class*	*Sample n*
Richmond Berm	Surface	6.5**b** (0.2)	57.55**c** (0.39)	21.27**b** (0.41)	21.18**c** (0.42)	Sandy Clay Loam	11
	Subsurface	7.3**a** (0.3)	41.67**d** (0.67)	29.33**a** (0.67)	29.00**d** (0.00)	Clay Loam	3
Section 2/8	Surface	6.2**b** (0.2)	85.93**a** (0.86)	5.87**a** (0.53)	8.20**a** (0.54)	Loamy Sand	15
	Subsurface	3.7**c** (0.2)	80.87**b** (1.21)	6.00**a** (0.39)	13.13**b** (1.16)	Sandy Loam	15
	Clay Barrier	3.8**c** (0.1)	0	0	100.00 (0.00)	Clay	9

*Means (± SE) within the same column and followed by the same bold letter are not significantly different at $p = 0.05$.

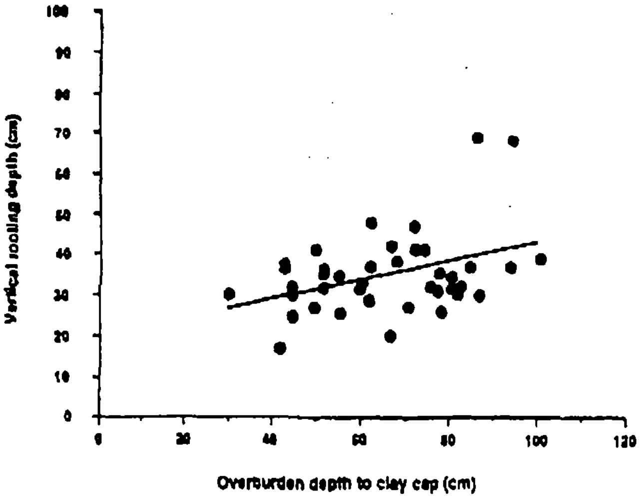

Figure 3. Maximum rooting depth (Y, cm) versus overburden depth (X, cm) for woody plants (all species combined) excavated on the capped landfill site after the 1993 growing season. The relationship between the two variables is described by the best-fit equation: $Y = 20.34\ (\pm 6.12) + 0.226\ (\pm 0.090) \cdot X$.

prising, because the fungal symbionts associated with roots of the grasses and legumes, which were planted on these sites to control erosion, are exclusively endomycorrhizal. All fine roots sampled on the berm showed signs of mycorrhizal infection, regardless of whether they were from ECM or VAM plants (Table 3).

Occurrence of infection was also tested with soil depth. Mycorrhizal infection was higher in the surface soil, even though responses for the top samples were underrepresented in the data set, compared with side and bottom sample categories (Table 4). Very low levels of mycorrhizal infection were found in roots from the bottom of the subsoil horizon on the landfill site.

Based on simple presence or absence, the proportion of roots exhibiting signs of mycorrhizal infection progressively decreased from the surface (71%), through the middle of the subsoil layer (45%), to the lowest roots in the subsoil layer (20%). There were no differences in the proportions of infected roots found in the subsoil along the sides of the root balls, compared to the bottoms (pairwise contrast, side versus bottom roots: $\chi^2 = 3.56$, $p = 0.059$), and the top samples (side versus top roots: $\chi^2 = 1.84$, $p = 0.175$). There was a significant difference in mycorrhizal infection, however, between roots in the topsoil and the lowest roots collected from the subsoil (top versus bottom roots: $\chi^2 = 6.64$, $p < 0.01$).

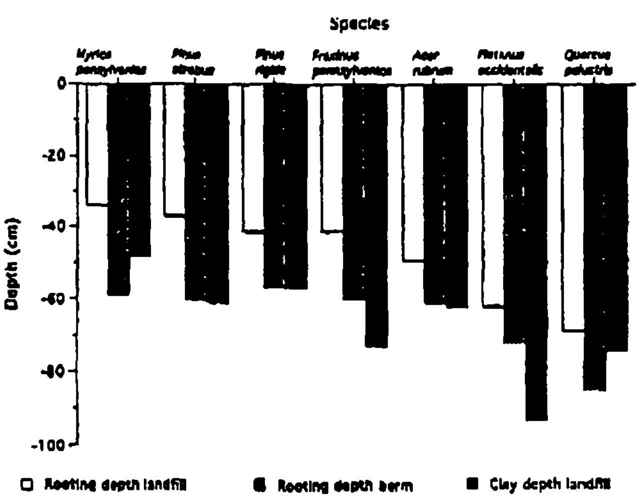

Figure 4. Maximum observed vertical rooting depth for seven tree and shrub species excavated in 1993 on the landfill and berm sites. Maximum depth of overburden to the capping clay associated with each of the individual woody plant excavations is also reported for each species.

Table 3. Infection of fine roots are taken from ectomycorrhizal (ECM) and endomycorrhizal (VAM) trees and shrubs excavated at two locations on the Fresh Kills Sanitary Landfill.*

		Location	
Mycorrhizal Type	*Occurrence*	*Landfill*	*Berm*
ECM	Absent	5 (8.5)	0 (0.0)
	Present	12 (8.5)	2 (2.0)
VAM	Absent	15 (11.5)	0 (0.0)
	Present	8 (11.5)	3 (3.0)

*Expected counts under the null hypothesis of independence between row (mycorrhizal type) and column (location) categories are maximum-likelihood estimates and are included in parentheses.

Discussion

Root Morphology in Engineered Soils

Root systems of woody plant species can generally be categorized as having one of three forms (Sutton & Tinus 1983): (1) a taproot form, which is characterized by a strong, central, vertical root stock; (2) the heartroot, with numerous primary and secondary laterals and ob-

Table 4. Occurrence of mycorrhizal infection (ECM and VAM data combined) with increasing soil depth on the capped landfill site.

	Position		
Occurrence of Infection	*Top*	*Side*	*Bottom*
Absent	2 (4.07)	18 (19.20)	12 (8.73)
Present	5 (2.93)	15 (13.80)	3 (6.27)

*Expected counts under the null hypothesis of independence between the row (occurrence) and column (position) categories are maximum-likelihood estimates and are included in parentheses liquely angled roots that can penetrate the soil to some depth; and (3) the flatroot type, which is plate-shaped, and where most of the vertical roots are shallow and fibrous. Species-specific differences in root morphology, however, may not provide an effective basis for selecting species appropriate for growth above a clay barrier. There is a complex interplay between genetically determined properties of root form (Wagg 1967) and environmental or abiotic factors, which constrain root-system spread, root density, orientation, and depth. These factors include soil mechanical resistance, moisture status, aeration, pH, and temperature, which are themselves extremely variable both temporally and spatially (Gregory 1987). With respect to engineered soils, root growth is plastic and, therefore, root-form distinctions blur. After early stages of seedling development, the roots of trees and shrubs will respond to soil properties rather than express an unalterable genetic developmental program, blind to environmental conditions.

The vertical development of root systems is markedly affected by conditions of soil texture and aeration, often showing greater variation within rather than among soil types (Preston 1942; Horton 1958; Taylor 1971; Dexter 1987). For example, heavy compaction in non-clay soils, such as mine spoils, has been given as an explanation for the lack of forest development on a variety of degraded sites. Occasionally, root systems of woody plants can exploit fractures, cracks, and joints in dense soil strata, allowing sinker roots to penetrate and subsequently explore lower soil horizons. But adverse chemical conditions, such as metal toxicity, salinity, or extreme values of pH, can represent a more effective barrier to both root proliferation at depth and establishment of associations with mycorrhizal and nitrogen-fixing symbionts (Stone & Kalisz 1991). Robinson and Handel (1995) reported the acid-generating sulfide clays, which are frequently employed in landfill capping operations in the New York metropolitan area, represent a particularly poor-quality substrate, inimical to root growth and penetration.

The interaction between the expanding root system and a soil medium that varies spatially and temporally between favorable and unfavorable conditions (e.g., hardpan formation, periodic anoxia due to flooding) will further determine if a prominent single taproot persists or if the plant adopts a heart-shaped or plate-shaped root form. Consequently, the better the quality of the overburden specified for closure, the more favorable this soil zone will be for lateral root development.

Design and Management Implications

Over 3 years of growth by a variety of woody plants, no damage to the clay cap barrier was observed, consistent with the results from the Brookfield landfill study (Robinson & Handel 1995). Like those species examined during that study, the woody plants excavated at Fresh Kills represented a wide array of potential growth forms. Many of the planted species certainly had the capability of extending vertical roots below the depth of the overburden placed over the clay cap (Stone & Kalisz 1991), yet all remained above the cap. Dobson and Moffat (1993) noted that tree roots were unlikely to grow into soil layers with inherently high bulk densities, which approach those recommended for an engineered clay cap (1.8–1.9 g cm^{-3}). Discontinuities in physical structure between the clay barrier and hydraulic protection layer can inhibit downward root extension, not only through large differences in bulk density between the soil layers, but also through abrupt reduction in the size distributions of the available pore spaces (Dobson & Moffat 1993). As a reduced pore volume leads to limited gas diffusion and exchange, root growth in these zones can be physiologically as well as physically impeded.

The relatively restricted root growth at Fresh Kills can be interpreted as additional evidence that root form of these species is plastic, and that vertical proliferation of roots will occur more strongly under benign soil conditions, as observed on the Richmond Avenue berm. In addition to no plant roots growing through or into the capping clay, roots above the clay exhibited dep d growth when compared to identical plants in m a-vorable soil (e.g., Fig. 4).

Similarly, the overall incidence of mycorrhizal infection was low in the landfill cover materials, but it would appear that the presence or absence of mycorrhizal infection was more important than the degree of infection of roots in the subsurface and surface soil layers. Endomycorrhizal fungi are much less specific than ECM fungi in terms of their host plant associations, but there may also be a "mismatch" between endobiont and host: VAM fungi encountered in the landfill cover material may more readily infect the herbaceous plant species present than the woody species that were installed on the sites. Moreover, the intensity of VAM infection has been shown to decrease as available soil phosphorus decreases (Allen 1991). High extractable phosphate and nitrate concentrations may be a common feature of cover soils in this landfill complex (W. F. J. Parsons and J. G. Ehrenfeld, unpublished data).

We interpret the decrease in the percentage of overburden occupied by roots as a response to the much wetter soil conditions at the bottom of the slope (to the extent that many wetland species such as rushes and sedges have naturally invaded only the lower slope). The woody roots of most installed plant species will not invade waterlogged soils, and they remain in th -saturated upper layers. Consequently, the roots a e lower slope positions were kept even more distant from the clay cap because of hydrologic constraints. As Dobson and Moffat (1993) noted, even species that are adapted to flooding, such as *Acer rubrum*, had poor growth performance when their root systems were installed in landfill cover materials subjected to waterlogging. In our study, many roots taken from the bottom of the subsurface horizon were moribund or dead, and given the extremes of pH and anoxia (as suggested from the rod data) that characterize this environment, it is not surprising that the incidence of mycorrhizal infection was zero or near zero.

Because the clay barrier layer is not only nutrient-poor but also inhibits nutrient uptake (by acidifying the root-soil interface or sequestering nutrient ions within clay interstices), root growth into capping clays (especially pyritic clays) should be minimal. Also, unlike results reported from the Brookfield landfill (Robinson & Handel 1995), the pH of soil beneath individual plants excavated on Section 2/8 was at least as low as that of the underlying clay, suggesting acidification of the sandy protection layer by the clay cap. Other properties of this clay (such as high sulfide concentrations and mobilized heavy metals are as Fe, Mn, and Al) create a toxic local environment that retards root growth. The blackening of the lower portions of the rods, especially those implanted near the base of the slope, was likely attributable to sulfide production (Carnell & Anderson 1986) and, therefore, is indicative of a strongly anaerobic environment.

Minor cracks, breaches, or other discontinuities in the clay cap (e.g., incurred by slumping or subsidence) might be sites of root penetration if they are not repaired. Based on our understanding of the engineered soil profiles such as those employed at municipal landfills, however, even this type of root penetration should be minor, because the cap is overlain by a layer of anoxic, nutrient-poor sand, often suffused with methane, carbon dioxide, hydrogen sulfide, and other metabolically inhibitory gases. Thin, probing taproots might penetrate through breaks or pores in the clay cap. But these fissures or breaks are "hot spots" for unregulated effluxes of landfill gases through the cover materials; continual outward diffusion of methane contributes to anaerobiosis through mass displacement of other gases from the soil atmosphere and through oxygen consumption by methanotrophic bacteria (Dobson & Moffat 1993). Roots would be expected to die back or cease growth in this type of inhibitory microenvironment, and not expand in length or girth as would be expected in a benign soil environment. Studies conducted by the Environmental Protection Agency have clearly shown the damage to plants growing in high concentrations of noxious landfill gases (Flower et al. 1977). Rather than the plant challenging the landfill cap, the net result would be that the plant itself is challenged.

Acknowledgments

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Forest Sci., Vol. 27, No. 4, 1981, pp. 660–666

Root Penetration of Douglas-fir Seedlings into Compacted Soil

PAUL HEILMAN

ABSTRACT. This experiment was designed to examine the relationship of soil compaction to root growth in one sandy loam and two loam soil materials. The experiment was conducted under controlled environment using test cores of experimentally compacted soils ranging in bulk density (BD) from 1.3 to 1.77 g/cm³. Root penetration of 35- to 45-day-old seedlings varied considerably among seedlings but generally declined linearly with increase in BD (r^2 for each soil varied from 0.60 to 0.71). Using the regression equations, the values for BD estimated to prevent root penetration by most seedlings, varied from 1.74 to 1.83 g/cm³. These values are higher than previously reported for Douglas-fir but generally compare to those reported for other plants in loam soils. The corresponding pore space at which rooting was prevented varied from 30 to 27 percent. When downward growth was restricted by high BD most roots grew laterally in the uncompacted surface soil to a greater total length than they grew vertically at the lowest BD level. Top growth of seedlings in this experiment was not significantly affected by BD. Root impedance in relation to effects of compaction and variability of root penetration among seedlings are discussed. FOREST SCI. 27:660–666.

ADDITIONAL KEY WORDS. *Pseudotsuga menziesii*, soil bulk density, total soil porosity.

REDUCED GROWTH OF TREE SEEDLINGS in soils compacted by vehicular activity has been demonstrated in field studies with loblolly pine (Hatchel and others 1970) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Youngberg 1959, Froehlich[1]). Soil compaction has similarly reduced root growth and root penetration in pot studies with loblolly pine (*Pinus taeda* L.) (Foil and Ralston 1967) and Douglas-fir and western hemlock (*Tsuga heterophylla* Raf. Sarg.) (Pearse 1958). Even a relatively minor increase in soil density can have significant adverse effects on tree seedlings. For instance, Froehlich[1] found 12 to 20 percent reduction in height growth of 4- and 5-year-old planted Douglas-fir where soil compaction produced only an 8 to 10 percent increase in bulk density (BD). The BD values after compaction in that study were around 1.0 g/cm³. Reduced root growth at that BD was also observed by Pearse (1958) with Douglas-fir seedlings on a sandy loam soil. Results of the study by Foil and Ralston (1967) with loblolly pine show similar results with both root length and root weight decreasing linearly with increase in BD above about 0.9 g/cm³.

Other workers investigating the relationship of root growth to soil compaction have been concerned with determining the upper limit of soil compaction for root

[1] Froehlich, H. A. (Not dated.) The effect of soil compaction by logging on forest productivity. Forest Eng Dep, Oreg State Univ, Corvallis, final report to Bur Land Manage, Portland, Oreg.

The author is Forest Scientist, Western Washington Research and Extension Center, Puyallup, Washington 98371. Scientific Paper No. 5628, Project No. 0531, College of Agriculture Research Center, Washington State University, Pullman. The author is grateful to Christine Skjerping for assistance on this project and to William Scott and H. A. Froehlich for review of an early draft of this manuscript. Manuscript received 8 May 1980.

TABLE 1.

Property	
Texture class	
Sand .... percent ..	
Silt .... percent ..	
Clay .... percent .	
Field bulk density .... g/cm³ ..	
Particle density .... g/cm³ ..	
pH	
Organic matter ...... percent ..	
Kjeldahl N .... percent ..	

[1] Spoils after mining.

penetration. That limit was
cm³ for western redcedar t
glacial till (Forristall and Ge
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MATERIALS AND METHODS

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[2] Scott, W. Weyerhaeuser Rese

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TABLE 1. Properties of three soil materials.

Property	Melbourne-Centralia	Salkum-Prather	Weathered subsoil
Texture class	Loam	Loam	Sandy loam
Sand .... percent ..	54	47	56
Silt .... percent ..	27	29	30
Clay .... percent ..	19	24	14
Field bulk density .... g/cm^3 ..	1.32 ± 0.06	1.33 ± 0.08	[1]1.52 ± 0.12
Particle density .... g/cm^3 ..	2.52	2.50	2.47
pH	5.0	5.3	4.8
Organic matter ...... percent ..	2.7	1.8	0.3
Kjeldahl N .... percent ..	0.065	0.047	0.012

[1] Spoils after mining.

penetration. That limit was estimated to be 1.25 g/cm^3 for Douglas-fir and 1.8 g/cm^3 for western redcedar based upon root distribution in soils on compacted glacial till (Forristall and Gessel 1955). A higher limit for Douglas-fir, about 1.45 but less than 1.59 g/cm^3 was found in pot studies with seedlings in a sandy loam (Minore and others 1969). The differences that have been reported in effects of compaction and bulk density on root growth can be attributed to a variety of factors. These can include differences in texture and soil particle density. Because of the effect of soil particle density on bulk density, percent pore space rather than BD is recommended as an index of soil compaction (Scott[2]).

The objective of this study was to examine the effect of compacted soil on impedance of roots of Douglas-fir seedlings. I was interested not only in the upper limit of soil compaction for root penetration but also the relationship of root growth to variation in soil density.

Materials and Methods

The three soil materials used in this study were (1) mixed topsoil of Salkum series, (2) mixed topsoil of Melbourne-Centralia series, and (3) weathered Skookumchuck formation sandstone subsoil (Table 1). They represent topsoil and subsoil materials associated with an open-pit coal mine operation near Centralia, Washington. These soil series are fairly extensive in southwestern Washington. The Salkum series was formed from highly weathered glacial till parent material (the Logan Hill formation) and the Melbourne and Centralia series were from Tertiary siltstone and sandstone parent materials (the Skookumchuck formation). Similar sedimentary rocks of Tertiary age are widespread in Washington and Oregon (Snavely and others 1958). At the coal mine, the weathered zone Skookumchuck formation sandstone is yellowish brown and has an average depth of about 7 m and a maximum depth of about 20 m. The subsoil sample was a composite of the entire depth of weathered material. The two topsoil samples consisted of composites of A and B horizons comprising roughly the top 60 cm in these soils. The materials used in this study were collected from two topsoil storage piles, one obtained from an area with Salkum series and the other from an area of Melbourne and Centralia series. The methods of removal of topsoil

[2] Scott, W. Weyerhaeuser Research Center, Centralia, Wash. Personal communication.

and placement in the storage piles result in a high degree of mixing, nevertheless care was taken to assure the collection of representative samples. All reported analyses were on the composite samples as collected

Experimental treatments consisted of the three soil materials, two soil moisture levels, three levels of soil compaction with two replications.

The soils were collected wet and were partially dried in the laboratory and then sieved through 0.6 cm mesh screen. The two moisture levels comprised (1) moist soils with 15.0 ± 1.2 to 19.8 ± 0.5 (standard deviations) percent water on a dry weight basis and (2) wet soils with 17.2 ± 0.3 to 21.3 ± 0.9 percent water. The wet soils were obtained by adding water to half of each soil and allowing the water to equilibrate with the soil for 1 week. Curves of soil water potential vs. percent soil moisture content were determined for the three soil materials (Campbell and others 1973). Using these curves, water potential for moist soils was estimated to vary from 0.2 to 0.7 bar and in wet soils from 0.1 to 0.4 bar depending upon soil type and compaction level. Water potentials in the Centralia-Melbourne soil were lower than in the other two soils.

The variation in BD was obtained by compressing soil with a Carver hydraulic press (Fred S. Carver, Inc., W142 North, 9050 Fountain Blvd., Menomenee Falls, WI 53051). The pressures needed to obtain desired BD's were determined for each soil moisture level in preliminary testing. Compaction pressures varied among soils and soil moisture levels between 4.9 and 9.8 kg/cm² for low compaction, 13.6 to 29.2 kg/cm² for intermediate compaction, and 34.4 to 93.5 kg/cm² for high compaction. Higher pressures were required with the finer textured Salkum soil and for the lower soil moisture levels. Final BD values were calculated for each plot from measurement of volume and weight of the soil after compaction and thus the values are means for the test cores. Uniformity of compaction within the individual cores was not evaluated.

The soil was compressed into 10-cm-long cylinders cut from 7.7-cm diameter polyvinylchloride pipe with a wall thickness of 0.6 cm. These cylinders formed the planting containers. The quantity of soil added to each was 250 g (oven dry basis). The compacted soil occupied the bottom 3.0 to 3.9 cm of the cylinders.

Stratified seeds of Douglas-fir collected from low elevation in Cowlitz County Washington were sown on the surface of the soils immediately after compaction. Twenty-three seeds were used in each cylinder. The seeds were then covered with 100 g of loose soil of the same kind and moisture content. The soil covering was then lightly tamped to a density of 1.2–1.3 g/cm³ and an approximate depth of 1.7 cm. To maintain soil moisture and prevent soil shrinkage, the ends of each cylinder were covered with polyethylene film fastened with rubber bands. Clear 2 mil plastic was used on the top end to provide light entry for the seedlings. This arrangement allowed the level of the upper plastic to be raised as more space was needed for height growth of the seedlings. Black 1.5 mil plastic was used on the lower end of the containers. Soil moisture loss was negligible over the course of the experiment. Moisture levels in the soils averaged 19.0 percent initially and 18.8 percent at the end of the experiment.

The seeding containers were placed in a controlled environment chamber, half incandescent and half fluorescent lighting initially providing 17 h per day of 2,150 lux of illumination. This was increased to 3,550 lux 18 days after planting. Temperature was controlled at approximately 21°C and relative humidity was maintained at 85–90 percent to help minimize the loss of moisture from the containers. No water was added to the soils during the experiment and the plastic was not removed during the course of seedling growth.

Seedlings were harvested starting 35 days after planting and continuing for the next 10 days. For harvest the soil was removed from the cylinders by first cutting through the sides of the cylinders with a bandsaw. Measurements of emerged seedlings included length of stem and roots. Root measurements included total

FIGURE 1. Root penetration b
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Results and Discussic

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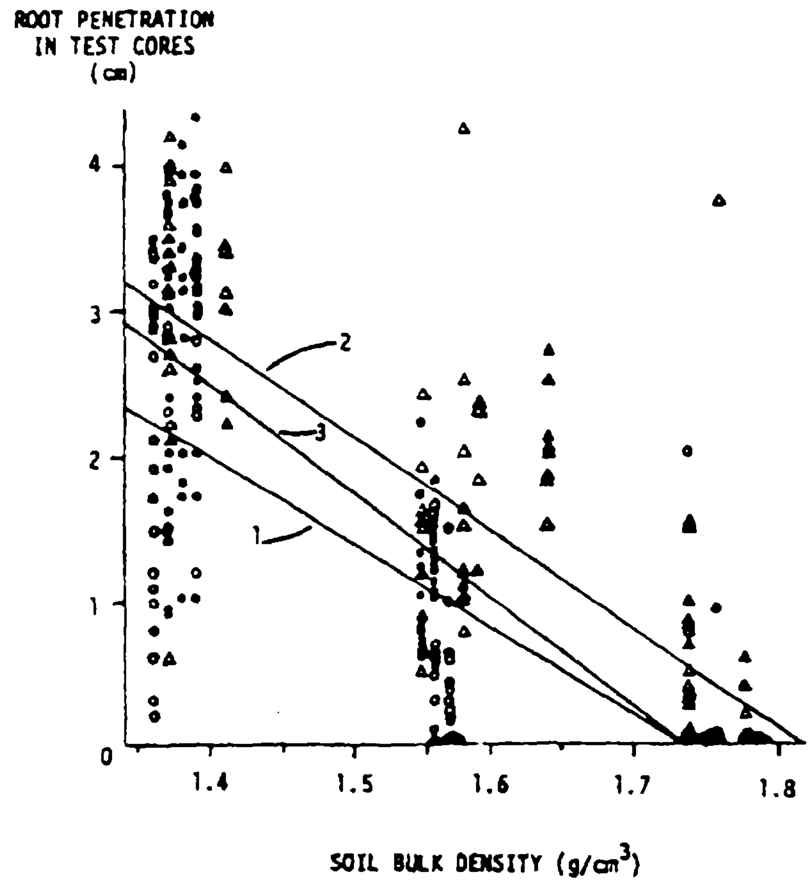

FIGURE 1. Root penetration by Douglas-fir seedlings in compacted test cores in relationship to bulk density. Regression equations for each soil are as follows: (1) Salkum (open dots) $y = 10.19 - 5.87x$ ($r^2 = 0.60$, $P = 0.0001$); (2) Melbourne-Centralia (triangles) $y = 12.00 - 6.55x$ ($r^2 = 0.63$, $P = 0.0001$); (3) weathered subsoil (solid dots) $y = 12.79 - 7.35x$ ($r^2 = 0.71$, $P = 0.001$).

length of the primary root (whether or not it penetrated the test layer of soil), length of primary root penetration into the test layer of compacted soil and finally vertical penetration of the primary root into the test layer of compacted soil. Soil moisture content was determined at time of harvest.

Statistical analysis of data was by analysis of variance (ANOVA) and Duncan's multiple range test (DMRT) at the 5 percent level of significance.

Results and Discussion

Harvest and measurement of seedlings were done randomly within each replication in order to minimize the effect of time of sampling on the results. Mean harvest day for the 3 bulk density treatments ranged from 5.6–6.1 days, for the 3 soils 5.6–6.0 days, and for the 2 moisture levels 5.5–6.1 days.

Both total penetration and vertical penetration of primary roots in test layers of compacted soils were significantly reduced by increased BD according to ANOVA ($P \leq 0.0001$).

Regression analysis showed that primary root penetration into compacted soils declined linearly with increase in BD ($r^2 = 0.80$–0.86; Fig. 1). Linear decreases in root penetration and growth with increase in BD were reported for corn (Phil-

TABLE 2. Effect of soil compaction on length of primary root penetration in compacted soil.

Soil material	Length of primary root penetration in compacted soil			
	Least compact (BD 1.38 g/cm³)	Intermediate (BD 1.57 g/cm³)	Most compact (BD 1.76 g/cm³)	Mean
	cm/seedling			
Melbourne-Centralia	3.85 a[1]	2.25 b	1.09 c	2.35 a'
Salkum-Prather	3.26 a	1.28 c	0.06 d	1.68 b'
Weathered subsoil	3.49 a	1.30 c	0.07 d	1.89 b'
Mean	3.51 a'	1.61 b'	0.46 c'	

[1] Values and means not followed by the same letter are significantly different according to Duncan's multiple range test ($P \leq 0.05$).

lips and Kirkham 1962), apple trees (Webster 1978), and certain conifers (Pearse 1958, Foil and Ralston 1967).

Root penetration data for the three soils is shown in Figure 1 along with the regression lines. Wide variation is evident particularly at the two lower compaction levels. Here much of the variation was due to differences in seedling vigor since values for all emerged seedlings were plotted regardless of seedling size. Variation at high bulk density is more important since, if these roots were not following soil cracks or zones of lower resistance at the interface of the soil and the container, it suggests that individual plants are capable of rooting in soils too dense for the majority of the population. Such avenues for root penetration were not evident, in keeping with the measures taken to prevent moisture loss, nor did the roots penetrating compacted soils appear to be following such pathways.

Using the regression equations, estimates were made of average BD values restricting root penetration for most seedlings in the various soils. These were Melbourne-Centralia 1.83 g/cm³, Salkum 1.75 g/cm³, and weathered subsoil 1.75 g/cm³. These values are considerably higher than the maximum of 1.59 g/cm³ for Douglas-fir root penetration reported by Minore and others (1969) for a sandy loam soil under differing experimental conditions. The values from this experiment generally correspond to the upper limit for root penetration by apple trees in loam and sandy loam soils (Webster 1978) and for sunflowers in loams (Veihmeyer and Hendrickson 1948). Data on primary root length in compacted soils (Table 2) show significant differences in rooting among soils in both average root growth and the effect of BD on root growth. The Melbourne-Centralia soil with higher organic matter and also lower average moisture potential was less restrictive to root penetration than the other two soils.

Seedling heights were not significantly affected by BD. Seedling heights were significantly higher in the two topsoils (6.55 and 6.41 cm) than in subsoils (5.69 cm). Taller seedlings were found in wet soils (6.38 cm) than in moist soils (6.01 cm). Thus, in this experiment, effect of soil compaction on root penetration was not reflected in top height of seedlings, contradicting the work cited earlier for older, field-grown seedlings by Hatchel and others (1970). However, seedlings in this experiment utilized the loose upper layer of soil, particularly those from the most compacted treatment. Table 3 shows total lengths of primary roots were considerably greater at the highest level of compaction. The restriction on downward root penetration at highest compaction apparently stimulated root elongation into the loose upper layer with a concurrent loss of geotropism. Many of these roots grew on top of the compacted soil along the interface of the soil and the plastic container. At the highest compaction the longest primary roots grew

TABLE 3. Effect of soil ... pacted soil and in the no...

Soil material	L... (B...
Melbourne-Centralia	
Salkum-Prather	
Weathered subsoil	
Mean	

[1] Values and means not follo... multiple range test ($P \leq 0.05$)

in the Salkum soil and th penetration at high com adaptation of roots to th

Relatively high soil m of moisture (0.1–0.7 bar significant interaction o moisture did not signific vertical root penetratior length in the compacted moisture level. Mean pr and 1.83 cm for wet anc cantly different accordin have increased the effec enced more by soil mois Relatively high moisture the effect of soil density

Values from this expe very young Douglas-fir in the field. However, f penetration in compact likely to limit root grov whereas mechanical im tured and well-drained the limiting of Douglas- at BD of 1.25 g/cm³ (F or reducing conditions experiment. The range reported in the field o values have been meas

The total percent pc seedlings was 27 perce subsoil and Salkum soi tion and the particle d highest values for poro growth in apple trees t

Of perhaps more sig to root penetration is 1.37 and 1.77 g/cm³. Tl

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lling heights were ı in subsoils (5.69 ı moist soils (6.01 ·t penetration was ‹ cited earlier for ever, seedlings in ·ly those from the imary roots were triction on down- ated root elonga- ropism. Many of ce of the soil and imary roots grew

TABLE 3. Effect of soil compaction on the total length of primary root in compacted soil and in the noncompacted surface layer.

Soil material	Total length of primary root			
	Least compact (BD 1.38 g/cm³)	Intermediate (BD 1.57 g/cm³)	Most compact (BD 1.76 g/cm³)	Mean
	cm/seedling			
Melbourne-Centralia	3.93 b[1]	2.31 c	4.37 b	3.58 a'
Salkum-Prather	3.27 bc	3.29 bc	6.33 a	4.19 a'
Weathered subsoil	3.51 b	2.13 c	6.23 a	3.91 a'
Mean	3.55 b'	2.60 c'	5.56 a'	

[1] Values and means not followed by the same letter are significantly different according to Duncan's multiple range test ($P \leq 0.05$).

in the Salkum soil and the subsoil, both of which were the most restrictive to root penetration at high compaction. Such a response by these roots may indicate an adaptation of roots to the restriction of downward root penetration.

Relatively high soil moisture in this experiment together with the narrow range of moisture (0.1–0.7 bars) resulted in a relatively minor effect of moisture and no significant interaction of moisture × BD on root growth and penetration. Soil moisture did not significantly affect total length of primary roots ($P \leq 0.297$) or vertical root penetration in the compacted layer ($P \leq 0.085$), but primary root length in the compacted layer was significantly greater ($P \leq 0.031$) with the higher moisture level. Mean primary root lengths per tree in compacted soils were 2.13 and 1.83 cm for wet and moist soils respectively. These values were not significantly different according to DMRT. Somewhat drier moisture levels would likely have increased the effect of moisture on root growth since soil strength is influenced more by soil moisture at lower moisture levels (Taylor and Gardner 1963). Relatively high moisture levels were used in this experiment in order to evaluate the effect of soil density on root penetration when soil strength is lowest.

Values from this experiment for the upper limit of BD for root penetration by very young Douglas-fir seedlings are higher than reported for older Douglas-fir in the field. However, factors other than mechanical impedance often limit root penetration in compacted soils under field conditions. Anaerobic conditions are likely to limit root growth in compacted finer textured and poorly drained soils whereas mechanical impedance is more likely to limit root growth in coarse textured and well-drained soils (Webster 1978). An example of the former case is the limiting of Douglas-fir roots in a poorly drained, relatively fine-textured soil at BD of 1.25 g/cm³ (Forristall and Gessel 1955). No evidence of poor aeration or reducing conditions was evident in the cores of the compacted soil in this experiment. The range of levels of compaction in this experiment have been reported in the field on log skidding trails (Youngberg 1959) and even higher values have been measured on coal spoils (unpublished data by the author).

The total percent pore space (PS) at which rooting was prevented for most seedlings was 27 percent in Melbourne-Centralia and 30 percent in weathered subsoil and Salkum soils. The PS was calculated from BD limiting root penetration and the particle density (PD) of each soil: $PS = 100(1 - BD/PD)$. The two highest values for porosity are similar to porosities reported to be limiting to root growth in apple trees by Webster (1978).

Of perhaps more significance to rooting and tree growth than the upper limit to root penetration is the linear decline in rooting with increase in BD between 1.37 and 1.77 g/cm³. Thus, any increase in BD within that range will likely cause reduced rooting. Relatively minor compaction at BD's even lower than above significantly reduced Douglas-fir growth in the field (Froehlich[1]).

Results of this study indicate need for more field study of the effects of soil compaction on Douglas-fir root and top growth. More study is also needed of various measures such as ripping and subsoiling for reducing adverse affects of compaction in disturbed soil areas.

The apparent wide variation in the ability of Douglas-fir seedlings to root in compacted soils has received little attention by forest geneticists. If such variation is verified, seedling selection for tolerance to soil compaction could provide a new approach to the problem of soil compaction on forest lands.

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Forest Sci., Vol. 27, No. 4, 1981, pp. 667-

Bulk Densities
and Their Appl

Abstract. Bulk densities o
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modeling. Dominant fuel grou
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The author is Research Fore
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Windthrow
and
Pit and Mound Microtopography

Old-growth forests, by definition, are relatively natural and have been influenced by a variety of natural disturbances. In the eastern deciduous forest in general, and in West Virginia's mountainous mixed-mesophytic forest in particular, windthrow is a common occurrence. Occasionally, large patches or "stands" blow over, leaving few standing canopy trees, but more commonly one or a few trees will blow over, forming a small canopy gap. As trees blow over, often their huge root systems get uprooted and violently torn from the forest floor, leaving a large mound of mineral (subsurface) soil immediately adjacant to the resulting pit. This *process* is complex, and is influenced by a number of factors, including the physical crown and stem condition of the tree(s), the position of the tree(s) in the canopy, density of the canopy, surface and subsurface soil conditions, past disturbance, wind direction / speed / duration, and many other factors. Thus, it is very difficult to predict the spatial and temporal *patterns* of windthrow disturbance, and it is often assumed to be a random or stochastic process (that is, the resulting pattern of windthrow cannot readily be differentiated from a random pattern). This doesn't necessarily mean it *is* random, but rather that we can't yet statistically tell it apart from a random pattern.

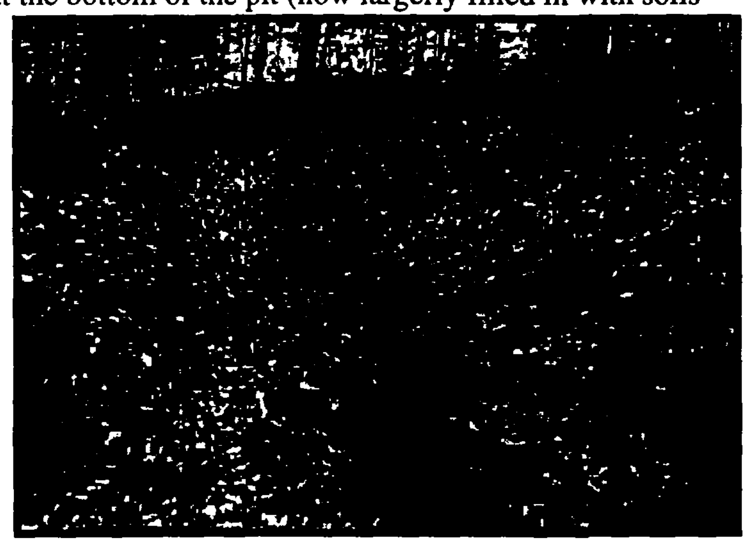
The pit and mound microtopography that results from windthrow is a natural and characteristic physical feature of most old-growth forests (although by no means an expert, I havn't experienced an old-growth forest that didn't have pit and mound microtopography). This doesn't mean that, by itself, pit and mound topography indicates old-growth status; in fact, most forests that havn't been plowed or otherwise altered by intensive agriculture (heavy forest grazing, for instance) have pits and mounds. Old-growth forests, however, typically have a *higher density* of pits and mounds relative to second-growth forests. Therein lies the difference - much like the other characteristics associated with old-growth status, *the measure is one of degree* rather than a simple absolute (a continuous versus a discrete measure).

Pits and mounds in the soil have an influence on the understory biotic community in a variety of ways. Certain species, for instance, are positively associated with mounds, while others are more common in pits. Mound soils tend to be relatively dry, while pit soils are often more moist; pH may differ as well, with mounds often being more acid than their companion pits. Note that pits and mounds do not exists by themselves, but rather result from an opening in the canopy, a "canopy gap". The uprooted windthrow not only creates a new substrate for colonization, but also exists in an area that is typically higher in direct beam radiation, higher in soil moisture during the growing season, has warmer and drier air, and has a more extreme temperature flux, among other differences. Either in isolation or as factors in a complex process, the ecology of pit and mound dynamics provides a variety of challenging questions that relate pattern to process, and whose answers may help us to better understand old-growth forests.

In this picture, a recent, fairly typical windthrow provides an idea of the size that pits and mounds might take. The root-wad is still in the early stages of decay, and in a few years as the roots decompose and shed their mineral soils the mound will be fully formed. Some mounds form more or less instantaneously, while others form over several years; this one is probably somewhere in between the two extremes, and formed when a 160 year old white oak was blown over in a windstorm during the winter of 1995-96. This photo was taken in April of 1996; a year later the

mound is perhaps a foot lower and relatively broad. The pit that my son Reese is standing in is approximately 24" deep and about 6' wide. During the first summer, the pit was colonized by *Rubus* spp., S*assafrass* seedlings, and greenbrier (*Smilax* spp.), while very few plants invaded the eroding mound (mostly *Rubus*). These species are characteristc of disturbed soils and high light conditions; they are "early successional" and "disturbance-loving", growing and reproducing quickly in openings of various sizes. Windthrow mounds, and the canopy gaps that form over them, are probably the historical "niche" within which these early successional species evolved. Notice the downed log to Reese's right (upper left corner); perhaps anopening in the canopy from several years ago weakened the white oak, causing it to blow over sooner that it otherwise would have without the adjacent opening.

The windthrow mound at lower right is much, much older. It is probably between 75 and 100 years old, perhaps forming when one of the non-mechantable, non-harvested remnant trees blew over following the first cutting. Notice the patchy nature of the ferns growing in the pit, and the violets and other species growing on the mound (sorry about the quality of the photo - its another original slide). This photo was taken in a sugar maple-beech-basswood forest, a very rich site with a diverse understory.The plants growing in the strip at the bottom of the pit (now largerly filled in with soils



and organic matter) are Christmas fern (*Polystichum acrostichoides*); the herbs growing on the strip about halfway down the mound are *Viola* spp.. John Thompson (1980) found that certain herbs were associated with pits and mounds in an examination of herb colonization in three mesic old-growth areas, similar to the one in the picture, and others have found the same (Bratton 1976). Thompson's study focused specifically on frequency of occurrence and probability of colonization for windthrow pit-mound sites and fallen logs. He stimated colonization probabilities by sampling adjacent species and measuring their respective distances to the disturbed areas. His data suggests that species composition of pit-mounds probably results from short distance colonization by vegetative spreading and seed dispersal. Ants apparently dispersed many of the species that colonized mounds.

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GROWING TREES ON COMPLETED SANITARY LANDFILLS

*I A Leone, E F Gilman and F B Flower**

Introduction

Landfilling is recognised as probably the most convenient and economical method of solid waste disposal in the United States and throughout most of the world. Current practice entails the spreading of refuse on the ground in thin compact layers covered daily by an inert soil for the purpose of curtailing litter and water infiltration as well as to discourage insect and rodent infestation (BRUNNER and KELLER, 1972). The completed landfill (Figure 1), consisting of successive layers of horizontal cells, each 10 to 20 feet deep, topped by a final cover, reaches a considerable depth. Post closure plans for such sites preclude any that require excavation or the erection of permanent structures (FIRST, 1966; SOWERS, 1968). It is generally recommended that former refuse landfills be developed into parks, golf courses or other open-space recreational areas, most of which require the establishment of vegetation (ANON, 1965).

Brief History

A survey of close to 100 former landfills throughout the United States (FLOWER *et al*, 1977) has revealed numerous problems for vegetation, especially deep-rooted woody species, attempting to grow in such environments.

Although soil factors such as settlement, poor fertility, low moisture content and high bulk density winter injury and predatory animals accounted for many of observed failures in vegetation growth, the great majority of the cases of poor growth were attributable to the presence in the soil atmosphere of gases, particularly carbon dioxide (CO_2) and methane (CH_4) evolved through the anaerobic decomposition of organic wastes (FLOWER *et al*, 1978).

Previous to 1965, open burning was a common component of landfilling. While this created air pollution and vector control problems, the residual material was essentially non-biogradable and much less prone to settlement or gas development after landfill closure. Present day policy, however, prohibits open burning; and, hence there is more organic matter available for exploitation by gas-generating micro-organisms. Preliminary decomposition of organic fractions takes place through the activity of aerobic micro-organisms. Eventually, when the oxygen is depleted, anaerobes come to the fore and continue the decompositional process in the absence of free oxygen (ROVERS *et al*, 1959).

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TABLE 1. Landfill gases and possible concentrations in soil atmosphere.

Methane (60%)	Ethane (Tr)	Ethylene (Tr)
Carbon dioxide (85%)	Ammonia (Tr)	Propylene (Tr)
Carbon monoxide (Tr)	Hydrogen sulphide (Tr)	Hydrogen cyanide (Tr)

Excessive amounts of CO_2 in the soil have previously been reported to be phytotoxic (WIEGAND *et al*, 1959). Methane, though reputedly non-toxic *per se*, may limit soil O_2 through displacement or by serving as a nutrient source for methane-consuming bacteria which deplete the oxygen supply (HOEKS, 1972). Other gases known to be deleterious to plant growth such as ammonia, hydrogen, hydrogen sulphide, mercaptans, and ethylene (Table 1) may also be present in trace amounts.

The soil-contaminating gases may travel laterally as well as vertically. The first observation of injury to vegetation by landfill gas was made in corn and sweet potato fields of a farm in southern New Jersey located approximately 200 m from an actively operating landfill (FLOWER *et al*, 1977; LEONE *et al*, 1977).

Research Plan

The difficulty encountered in establishing successful plantings on landfills prompted the group at the New Jersey Agricultural Experiment Station to

TABLE 2. Species selected for vegetation growth experiment at Edgeboro landfill.

Latin name	Common name	Selection criteria*
Acer rubrum	Red maple	1, 2, 3
Euonymus alatus	Winged-euonymus	3
Fraxinus lanceolata	Green ash	1, 3
Ginkgo biloba	Ginkgo	3, 5
Gleditsia triacanthos	Honey locust	1, 3
Liquidambar stryaciflua	Sweet gum	3
Myrica pennsylvanica	Bayberry	1, 3
Nyssa sylvatica	Black gum	1, 3
Populus sp.	Poplar (hybrid)	3
Picea abies	Norway spruce	3
Populus sp.	Poplar (mixed hybrid)	
Platanus occidentalis	American sycamore	1, 3, 5
Pinus strobus	White pine	3
Pinus thunbergii	Black pine	3, 4
Quercus palustris	Pin oak	1, 3
Rhododendron roseum elegans	Rhododendron	3
Salix babylonica	Weeping willow	1, 3
Tilia americana	American basswood	3, 6
Taxus cuspidata capitata	Japanese yew	3, 6

*Selection criteria: 1. Tolerant of low O_2 environments. 2. Ubiquity. 3. Aesthetic landscaping purpose. 4. Sea salt tolerance. 5. Tolerant to city conditions. 6. Susceptibility to landfill gases.

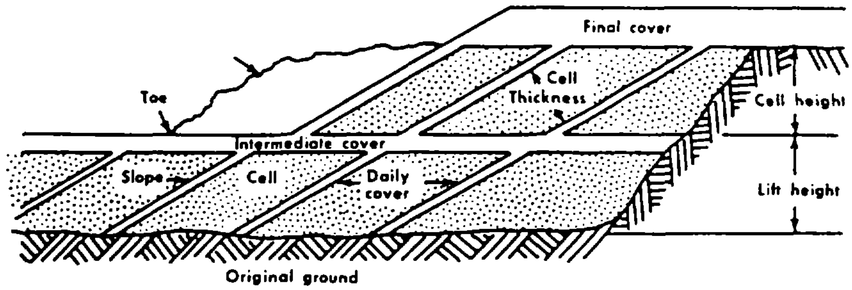

FIGURE 1. Diagram of a typical sanitary refuse landfill showing successive layers (lifts) of horizontal cells containing compacted refuse (BRUNNER and KELLER, 1972).

initiate research. Foremost among the objectives was a screening test to identify woody species capable of surviving the harsh environment of landfill cover soils.

An appropriate site for the experiment was located on a tidal marsh adjacent to the Raritan River, approximately 1.5 km from Cook College Campus in New Brunswick, New Jersey; which had been operated as a landfill and completed some 10 years earlier. A similarly exposed site in a non-landfill wooded area, approximately 450 m distant, served as a control.

The landfill, covering some 9 m of refuse, had received a preliminary 15-25 cm of soil cover at the time of closure. At the start of the screening experiment in

TABLE 3. Relative tolerance of species to landfill conditions.

Rank[a]	Species	Σ "t" Statistics[b]
1	Black gum	2.66
2	Norway spruce	3.22
3	Ginkgo	4.95
4	Black pine	6.59
5	Bayberry	6.62
6	Mixed poplar	8.13
7	White pine	8.94
8	Pin oak	8.96
9	Japanese yew	8.98
10	American basswood	9.48
11	American sycamore	10.66
12	Red maple	10.95
13	Sweet gum	12.62
14	Euonymus	14.25
15	Green ash	14.87
16	Honey locust	15.05
17	Hybrid poplar	20.33
18	Weeping willow	21.20
19	Rhododendron	All plants died

[a]Rank 1 = the best growth when experimental plot is compared to the control plot, ie, most tolerant of landfill conditions.
[b]Σ "t" = the sum of the "t" statistics for shoot length in 1976; leafweight, basal area increase, root biomass and shoot length in 1977 comparing the experimental area with the control.

March 1975 both landfill (726 m^2) and control (462 m^2) areas were cleared of debris and/or natural vegetation and 30 cm of sandy subsoil spread over each, followed by 15-25 cm of top soil.

Nineteen woody species were selected for screening on the basis of tolerance to low oxygen, sea salt, air pollution, urban conditions, and landfill gases; and for landscaping suitability or ubiquity (Table 2). Ten trees of each species were planted on each of the two sites in a nested design. The trees were routinely fertilised, limed, irrigated, pruned and generally maintained for four years. Although all the weeping willows (*Salix babylonica* L.), rhododendrons (*Rhododendron roseum elegans*), and euonymous (*Euonymus alatus* (Thunb.) Sieb.) in the landfill plot died by the end of the third year, presumably from lack of water, a majority of the trees survived.

Results of Experiments

On the basis of shoot length and stem area increase measured for each species on both landfill and control plots, the surviving trees were ranked in order of decreasing tolerance to the existing landfill conditions (Table 3). From these data, it appears that black gum (*Nyssa sylvatica* Marsh.), Norway spruce (*Picea abies* (L.) Karst.), and ginkgo (*Ginkgo biloba* L.) were most suited for growth on the landfill. Species tolerant to low oxygen environments: green ash (*Fraxinus lancolata* Borkh.) and honey locust (*Gleditsia tricanthos* L.) were located at the bottom of the tolerance list. Lack of sufficient moisture might have curtailed the growth of these water-loving species. Rapidly growing trees: hybrid poplar (*Populus* sp.), honey locust, and red maple (*Acer rubrum* L.) appeared to be less tolerant than slow-growers when growth on landfill was compared to growth of controls. However, the former species produced more absolute growth than the latter, so if amount of growth rather than relative growth were the criterion, red maple, honey locust and hybrid poplar might be considered for use on landfills.

FIGURE 2. Root system of hybrid poplar (*Populus* sp.) excavated from landfill cover soil containing high CO_2/CH_4 levels. Bottom-most root reached a depth of 15 cm before growing upward and branching into many shallow roots.

TABLE 4. Root depth of tree species in landfill and non-landfill (control) soils.

Species	Depth (cm) Landfill	Non-landfill
Norway spruce	5	4
Japanese black pine	7	9
Hybrid poplar (cuttings)	6	13
Hybrid poplar (saplings)	6	13
Honey locust	8	17
Green ash	9	15

Acid-loving species: Japanese black pine (*Taxus cuspidata capitata*), Norway spruce, black gum and bayberry (*Myrica pennsylvanica*) are more tolerant of the low pH (4.5) than are green ash, red maple and American sycamore (*Platanus occidentalis* L.).

Root systems of the more tolerant species (Japanese black pine and Norway spruce) were much shallower, both on the landfill and control, than were roots of the less tolerant species (Table 4). The ability to develop a shallow root system may be one of the overriding factors in the adaptability of trees to landfill conditions. Those more able to direct their root systems to a higher soil level (Figure 2) may thus avoid contact with the toxic or growth-curtailing gases produced in a landfill.

From a very limited amount of data, other factors which appeared to favour the chances for the survival of trees in landfill cover-soil were smaller trees at planting over larger trees of the same species, balled-and-burlapped roots over bare-rooted stock, extensive irrigation over poor irrigation, and gas-barrier systems such as soil mounds or lined and vented back-filled trenches over unmodified landfills (GILMAN *et al*, 1980).

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Philip P Gornicki and J*

Introduction

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EPA-600/2-79-128
August 1979

ADAPTING WOODY SPECIES AND PLANTING TECHNIQUES TO LANDFILL CONDITIONS

Field and Laboratory Investigations

by

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FOREWORD

The Environmental Protection Agency (EPA) was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment and management of wastewater and solid and hazardous waste pollution discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communication's link between the researcher and the user community.

The ultimate use of refuse landfills involves the planting of vegetation. The problems of growing deep-rooted vegetation over former landfills has been studied through literature surveys, and greenhouse and field experiments. It was the purpose of these studies to gain an insight into the role of anaerobically produced gases (mainly methane and carbon dioxide) in curtailing the growth of plants on landfills. Methods of attenuating the detrimental effects of landfill gases were also evaluated.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

During the past dozen years, many attempts to revegetate completed sanitary landfills have been undertaken throughout the United States, with variable degrees of success. This has been evaluated in a recent nationwide field survey of vegetation growth on completed sanitary landfills. Based on the results of this survey, literature reviews and other field experiences, a study was undertaken to determine which species, if any, can maintain themselves in a landfill environment; to investigate the feasibility of preventing landfill gas from penetrating the root zone of selected species by using gas-barrier techniques; and to identify the (those) factor(s) which are most important in maintaining adequate plant growth on completed sanitary landfills. Ten replicates of nineteen woody species were planted on a ten-year old completed sanitary landfill and five gas-barrier systems were constructed. The experiment was completely replicated on old forest land to act as a control. Of the nineteen species planted on the landfill for the past two years, certain species have tolerated the landfill conditions better than others. Black gum proved most tolerant and honey locust least tolerant to anaerobic landfill conditions. Of the five gas-barrier systems tested, plastic sheeting underlain by gravel and vented by means of vertical PVC pipes, a three foot mound underlain with one foot of clay, and a three foot mound with no clay barrier proved effective in preventing penetration of gas into the root systems of the test species.

Carbon dioxide and methane are the major components of sanitary refuse landfill-generated gas which has been associated with the demise of vegetation on and adjacent to completed landfills. An investigation of the effects of carbon dioxide (CO_2) and/or methane (CH_4) contaminated soil atmospheres on the growth of tomato plants indicated that CO_2 per se was toxic to tomato roots in a low O_2 soil atmosphere, whereas CH_4 per se was innocuous under the same conditions. No interaction was observed between CO_2 and CH_4 in terms of damage to tomato roots. Investigations into the effects of CO_2- and CH_4-contaminated soil indicated that red maple (Acer rubrum) is more tolerant to the presence of these gases than is sugar maple (Acer saccharum). With respect to gas concentration, 50% CH_4 alone in the root zone resulted in no visible symptoms whereas 20% CO_2 was found to cause adventitious root formation and visible decline in tomato shoots.

This report was submitted in fulfillment of Contract No. R 803762-02-3 by Rutgers University under the sponsorship of the United States Environmental Protection Agency. This report covers the period January 1, 1976 to September 14, 1978, and the work was completed as of October 15, 1978.

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SECTION 1

INTRODUCTION

The pressures of population expansion and urbanization have prompted a reappraisal of anticipated uses for completed landfill sites. Conversion to recreational areas or other non-structural usage has been considered an acceptable end for completed landfill sites in urban areas; and in rural areas intensifying land use has resulted in attempts to use completed landfills for growing commercial crops. Numerous farmers, as well as scores of landscapers, have encountered mixed success in trying to establish agricultural crops, trees, and shrubs on landfills throughout the country Three questions are often raised: "What species will thrive on completed landfill sites?", "Are there any techniques available which will help in attempting to establish a vegetative cover over a completed landfill area?", and "What is the nature of the toxic effect of landfill gas on vegetation?"

Reports from a nationwide mail survey funded by the Federal E.P.A. Solid and Hazardous Waste Division determined that the scope of problems encountered when vegetating completed landfills was indeed of national latitude. It was ascertained, from on-site visits to some 60 vegetated landfills, that answers to the previously raised questions would benefit not only the landscaper or farmer trying to vegetate a former landfill, but the general public as well in that they too would ultimately derive value from successful vegetation projects such as parks, golf courses and recreational areas.

In order to investigate the possibility of successfully growing vegetation on such areas, two experiments were designed: (1) a field experiment with three objectives: (a) to determine the relative tolerance of a number of commonly grown tree and shrub species to the soil environment created on and adjacent to a sanitary refuse landfill; (b) to determine if barriers to the migration of decompositional gases can function in preventing gas contamination of the root systems of selected sensitive species; (c) to identify those soil factors which are most responsible for causing vegetation growth problems on completed landfills. (2) A greenhouse experiment to assess the effects on vegetation of soil contamination by simulated landfill gas (CO_2 and CH_4) mixtures.

SECTION 2

CONCLUSIONS

1. Black gum, Norway spruce, and ginkgo were the three species most tolerant to conditions of the Edgeboro experimental landfill.

2. Honey locust, hybrid poplar, and weeping willow made the poorest growth of all surviving species on the landfill plot and appeared to be least adapted to landfill conditions.

3. Soil carbon dioxide, oxygen, moisture content, bulk density and temperature were important soil factors controlling the growth of American basswood on the experimental plot on the Edgeboro sanitary landfill.

4. Soil mounds, either with or without an underlying clay gas-barrier functioned successfully in preventing the migration of landfill gases into the root zone of trees. A 4-foot deep trench with a 1-foot layer of road gravel overlain with polyethylene sheeting and vented with perforated vertical vent pipes also functioned to keep out the gases of anaerobic decomposition.

5. Woody plants appeared able to better survive on a completed sanitary landfill if planted when small in height i.e. less than three feet. During this study, this factor appeared to be more important than the biological ability of a plant to withstand low oxygen environments.

6. Severe gas contamination of the original soil cover on the Edgeboro sanitary landfill was observed in isolated areas which could be located by the poor growth of vegetation associated with these areas. These soil gas conditions remained consistent for the fifteen month study period. The poor growth of vegetation in areas of landfill gas contamination was believed to be responsible for excessive erosion on the site.

7. Red maple (<u>Acer rubrum</u>), which is flood tolerant, was found to be more tolerant also of soil contaminated by simulated landfill gas than sugar maple (<u>Acer saccharum</u>) which is not tolerant of flooding.

8. Tomato plants growing in sand-solution greenhouse cultures were severely damaged by exposure to carbon dioxide concentrations of 17% or greater in the root zone. This response was not influenced by the presence or absence of high concentrations of methane or fluctuations in the O_2 concentrations, provided the O_2 in the root zone was not less than 2%.

9. Excessive concentrations of methane in the root zone of such tomato plants resulted in the depletion of oxygen, and the consequent decline of the plants after eight days' exposure.

10. Tomato plants exposed to excessive rhizosphere concentrations of carbon dioxide exhibited symptom development which differed significantly from that caused by lack of oxygen in the root zone, suggesting that high CO_2 concentrations damage tomato roots by a mechanism different from that of low oxygen concentration.

11. Rhododendron appeared to be poorly adapted to both landfill and control conditions.

SECTION 3

RECOMMENDATIONS

1. Those responsible for planting vegetation on completed landfills should avail themselves of current research on the adaptability of species to landfill conditions and avoid the use of non-tolerant species.

2. A survey of the landfill cover soil prior to establishing vegetation will help to avoid areas high in gas concentration for locating vegetation.

3. The use of a barrier technique for excluding landfill gas from the root zone of vegetation should be considered when planting on a former landfill. Two methods to consider would be (a) a mound of soil over the existing cover, (b) a lined and vented trench backfilled with suitable soil.

4. The use of smaller planting stock might also increase the chance of survivability.

5. Adequate irrigation of the plants established on a landfill is an important contribution to their survivability.

6. Special precautions should be taken to insure that the landfill cover soil has not been too densely compacted by heavy equipment. Loosening of the soil may be necessary before planting.

7. All cultural practices required for the successful establishment of vegetation in non-landfill soils should be considered, i.e. soil fertility, healthy planting stock, optimal soil density and physical characteristics, maintenance procedures, etc.

8. Further studies should be undertaken to determine if the ability to withstand high levels of carbon dioxide in the root zone is a characteristic of flood tolerant species.

9. The influence of secondary factors such as size of trees at planting, the use of bare-rooted versus containerized trees and the effect of water stress on the adaptability of species to landfill conditions should be evaluated.

10. The value of mycorrhizal fungi in inducing tolerance of trees to landfill conditions should be assessed.

SECTION 4

LITERATURE REVIEW

GAS PRODUCTION IN SANITARY REFUSE LANDFILLS

The serious disadvantages for adequate vegetation growth inherent in landfill sites; namely the production of toxic gas mixtures from anaerobic decomposition of organic matter present and leaching of infiltrates and gases into ground water supplies, as well as high ground temperatures, have been enumerated (32, 48, 160).

The composition of landfilled refuse varies considerably depending on its origin, be it municipal, industrial, incineration material or sewage sludge. The organic content of solid waste collected from homes, schools, commercial establishments and industries generally ranges from 50 to 75% on a weight basis. Most of these organics are biodegradable and can be broken down into simpler compounds by both aerobic and anaerobic organisms. The rate at which this occurs is reported to be a function of (a) permeability of cover material (b), depth of garbage (c) amount of rainfall (d) moisture content of the refuse, (e) putrescibility of the refuse (f) compaction (g) pH and (h) age of the landfill (i) redox potential (30, 87, 103, 138). The concentration of biocides as well as other factors may also effect the rate of decomposition.

When the refuse is initially deposited in the landfill, there is enough oxygen present to support a population of aerobic bacteria. This state lasts from one day to many months (49). The literature indicates carbon dioxide and water to be the principal products formed in aerobic decomposition (21).

After the oxygen concentration is depleted, the aerobic bacteria die, resulting in a sharp increase in the anaerobic bacterial population. During the anaerobic state of decompostion two phases have been identified, a non-methanogic state followed by a methane-producing stage (2).

During the non-methanogic stage, organic matter is reduced, in the presence of water and extracellular enzymes produced from bacteria, to smaller soluble components which include fatty acids, simple sugars, amino acids and other light--weight compounds (150). During the methanogenic stage, CO_2 and CH_4 are the principal gases produced. They originate from two reactions carried out by the bacterium Methano-bacterium (47).

Various other gases reportedly produced in the anaerobic environment of the landfill include ethane, propane, phosphine, hydrogen sulfide, nitrogen and nitrous oxide (3, 6, 14, 32, 96, 126, 150). Reserve Synthetic Fuel Company reports finding over 60 different gases in a California landfill (Frank Flower, Personal communication with Fred Rice, Reserve Synthetic Fuel Company March 15, 1977). Hydrogen sulfide which is produced from the bacterium Desulfovibrio desulfuricans in alkaline conditions (58), causes lower root respiration rates and a decrease in soil nematode population (84).

In addition to the methane-producing bacteria mentioned above, there exists a bacterium, Pseudomonas chromobacterium, which utlizes methane during its metabolism. It oxidizes methane, producing carbon dioxide and water (70). Since oxygen is required for this reaction, these bacteria will generally be found near the upper surface of the landfill.

During the oxidation of methane, oxygen is consumed. This raises a question of whether or not the oxygen concentration is a limiting factor in this reaction. Hoeks (70) points out that the organisms involved can function at soil atmospheric oxygen concentration as low as 1%. However, at this low concentration, incomplete oxidation causes formation of such intermediate side products as methanol, formaldehyde and formic acid (78).

Of the various factors influencing methane gas production, the parameters most commonly reported are refuse moisture content, temperature, oxygen and pH. Frequently the major factor is refuse moisture content. Ramaswamy (122) and Sougonuga (137) found that methane gas production rates increase with increased refuse moisture content, with a maximum production occurring at moisture content of 60 to 80% wet weight. Farquhar and Rovers (47) report maximum methane production when refuse is near the saturation point. An experiment carried out by Merz and Stone (99) concluded that methane gas production increased with the addition of surface irrigation water. Ludwig (94) found that at one of the two sites in California, methane production increased after a heavy rainfall. It is reported that refuse moisture content too low to support continuous gas production in a landfill may be in the range of 30 to 40% (99). This condition may exist in certain areas of the United States such as the dry southwest, where rainfall and relative humidity are very low.

Temperature has also been described as a limiting factor in the methane gas production. Kotze et al (82) report 37°C to be the optimum temperature for methane gas production in the mesophilic stage of sewage sludge decomposition. Dobson (37) and Ramaswamy (122) say maximum gas production occurs at 30°C and 35°C respectively. All found that deviations from the optimum temperature resulted in decreased methane production rates.

The optimum pH for methane production during anaerobic decomposition of sewage sludge is very near 7.0 (47). As deviations from this optimum are encountered, gas production is decreased. High pH may exist in the refuse because of the presence of alkaline materials. When methane production is inhibited, the information of organic acids results and the pH decreases (47).

EFFECT OF LANDFILL GASES ON PLANT GROWTH

Field Cases

Many reports of success or proposals for transforming barren former refuse sites into luxuriant vegetated areas have appeared in the literature and in the press (5, 12, 64, 88, 105).

In July 1972 an article by Duane (38) applauding the construction of golf courses on completed sanitary landfills cited the successful use of such tree species as Japanese black pine, London plane, thornless honey locust and Russian olive for beautifying the sites. In 1973, any anonymous article appeared in Solid Waste Management magazine describing the transformation "From Refuse Heap to Botanic Garden", of an 87-acre landfill in Los Angeles that the distinction of being one of the world's first such phenomena (4).

A catalogue published in 1973 describing hybrid poplars bred by a Pennsylvania nursery cites a particular hybrid which supposedly was grown successfully on a landfill site at Fort Dix, New Jersey (98). In that same year, a brochure was published by the Caterpillar Tractor Company describing and displaying in lavish color various successfully vegetated golf courses and parks in Mountain View, California; Anoka, Minnesota; Baltimore County, Maryland; Long Island, New York; Alton and Chicago, Illinois (24). In 1974 a news item in the Sun-Star of Merced, California described a 5-acre park whose new grass and trees would be aided in growth by "the proximity to the refuse which will provide needed nutrients" (6).

Few problems if any were either observed or anticipated in achieving these spectacular results with the exception of the report of root damage to large trees and shrubs at the Los Angeles Botanic Garden site.

At the same time, various investigators were experiencing difficulties in growing vegetation at similar sites. In January 1969, Professor F. Flower and associates of Rutgers University in New Brunswick, New Jersey (50), responding to a complaint of vegetation death on private properties adjacent to a landfill in Cherry Hill Township observed dead trees and shrubs of the following species: spruce, rhododendron, Japanese yew, azalea, dogwood, flowering peach, brush dogwood, Scotch broom, arbor vitae, Douglas fir, and lawn grasses. Testing of the soil with appropriate equipment disclosed high concentrations of carbon dioxide and explosive gases. The conclusion reached was that the trees and shrubs may have been killed by displacement of oxygen from their root zones by lateral movement of the gases of refuse decomposition or by the decomposition gases themselves.

In 1972, the Rutgers contingent made a visit to the peach orchard of the DeEugenio Brothers in Glassboro, New Jersey, which bordered on a completed landfill, where approximately 50 peach trees had died (51). Upon completion of the landfill, the growers had hoped to plant additional peach trees on the filled area. Examination of the soil atmosphere revealed high concentration of carbon dioxide and methane form the anaerobic decomposition of organic matter had moved laterally from the landfill into the orchard area.

The Hunter Farm, in Cinnaminson, New Jersey, was visited in December, 1974 when fields planted with rye were growing poorly (51). Gas checks revealed that combustible gases were present in the area of new vegetation injury and that migrating gases were traveling up to 600 feet from the nearest edge of the landfill.

Another trip to Hunter's Farm was made in June, 1975 when corn was found to be growing poorly in areas where combustible gas and CO_2 concentration were high.

On May 14, 1973, the Rutgers group visited Sharkey's Landfill in Parsippany-Troy Hills, New Jersey to estimate its potential for supporting vegetative cover and to examine field test plots set out by the county agent (53). It appeared that grass seeding had been attempted; however, grass seemed to be growing well over only small areas of the fill. Numerous pools of oily leachate were observed, many with gas bubbles breaking the surface.

Samples of soil gas revealed high concentrations of combustible gases. In the few areas where vegetation seemed to be growing well, there was little combustible gas in the root zone.

A communication from the county agent on June 3, 1975 reported that clover, vetch, lespedeza and weeping love grass were doing well on the landfill (79).

Although the literature on vegetation problems on completed landfills is fairly sparse, information received from a nationwide survey has indicated that such problems have been encountered throughout the United States. On-site visits (51, 52) to some of these areas in the northeast, the midwest, southern Alabama, the far west, Puerto Rico and southern California have corroborated the findings of the group at Rutgers University concerning the detrimental effect of landfill gases on vegetation atop or adjacent to completed sanitary refuse landfills.

The discrepancies in results of efforts to establish vegetation on former landfill sites is apparently due to variability in certain landfill characteristics such as type and amount of solid waste, depth and permeability of cover, construction and grading of the fill; certain meteorological conditions, such as temperature, relative humidity and rainfall, soil characteristics such as composition, texture, ability to retain moisture, nutritional characteristics; adaptability of plant species to landfill conditions, and planting and maintenance techniques to overcome unfavorable landfill conditions (17, 45, 123, 142, 154, 160).

Effect of Low Soil O_2 on Plant Growth

It has been known since the early 1900's that plants grown in solution culture required both air and minerals in order to achieve the best growth (44), this was found to be the case for barley, lupines (66, 127), and tomato (28, 41).

Chang and Loomis in 1945 (26) conducted a survey of the literature and found that although some plants could survive O_2 concentrations in the root zone as low as 1 to 2%, most plants would function normally at O_2 concentrations ranging from 5 to 10%.

There is a good deal of variability in tolerance to low O_2 in the root zone among different species of plants. The growth of red and black raspberries was inhibited by exposure to 10% O_2 (120), whereas apple trees required 10% O_2 in the soil in order to sustain growth (15). One-tenth percent O_2 in the flooded root zone of apple trees resulted in the death of the trees (15). Tomato plants grown in solution culture exhibited marked reduction in growth and ability to take up potassium when exposed to 3% O_2 in the root zone (153). Sour-orange seedlings in sand-solution culture given 1.5% O_2 in the root zone for seventeen weeks did not grow, and seedlings receiving 4.6 to 6.1% O_2 grew half as well as the controls (62). Rice plants have been reported to grow as well in solution culture having less than 1% O_2 in the root zone as control plants (153).

Aside from differences between species, environmental factors can also influence plant response to low O_2. High temperatures were found to increase the need for O_2 by growing root tips (120). A dense soil can also increase the need for O_2 by growing root tips. This is believed to be due to the extra energy required to push the root tips through the soil (61). The O_2 concentration in the soil is dependent on the ability of air to diffuse into and through the soil and the rate of diffusion is largely dependent on the texture and degree of compaction of the soil. Sandy soils generally exhibit ample gas exchange, whereas finely textured soils with pore spaces of less than 10% are prone to poor soil aeration (155, 161). Excessive compaction in soils containing large amounts of clay was found to result in O_2 concentrations of less than 2% and CO_2 concentrations as high as 20.5% (162).

Low concentrations of O_2 in the root zone can influence plants in ways other than by decreasing growth or killing the plants. Susceptibility of roots to soil-borne pathogens has been found to increase when the soil is poorly aerated. This is believed to be due in part to the ability of some pathogenic fungi and other organisms to flourish in such soils (8). Sustained low O_2 concentrations in the soil have been found to cause mineral deficiencies in plants. Potassium is the first mineral affected. The order in which the other major nutrients, nitrogen, phosphorus, calcium, and magnesium, become deficient depends upon the plant species (69, 78, 91).

Effect of High Soil CO_2 on Plant Growth

Carbon dioxide (CO_2) concentrations in the soil normally comprise less than 2% of the soil atmosphere. The death of vegetation in flooded or poorly aerated soils is not generally considered to be due to excessive CO_2 concentrations but rather to lack of oxygen (85). CO_2 concentrations as high as 20.5% have been reported in the soil under roadways and compacted paths in areas where trees were reported to have been killed, but the high CO_2 readings occurred in conjunction with very low O_2 concentrations (162).

In a sanitary landfill, the refuse is a source of CO_2 which can migrate into the surrounding soil, resulting in concentrations greater than 20% (52). The CO_2 migrating into the soil can displace the O_2, but not being dependent on the soil O_2 for its generation, it can occur in high concentrations in conjunction with O_2 concentrations which might not be considered limiting to plant growth.

Plant species vary in their sensitivity to excessive CO_2 in the root zone The exposure of plant roots to pure CO_2 was first shown to be toxic in 1914 (109). Pure CO_2 in soil around tomato and corn plants killed the plants after two weeks exposure (109). This was also found to be true for buckwheat which was killed after a few days' root exposure to pure CO_2 (56). The growth of guayule in solution culture exhibited a significant reduction (20), and red and black raspberries were killed when exposed to 10% CO_2 in the root zone (120). Cotton plants growing in solution culture exhibited optimum growth in the presence of 10% CO_2 in the root zone, provided at least 7.5% O_2 was also present. Thirty to 40% CO_2 in the root zone severely limited growth, and 60% CO_2 stopped growth of cotton completely (90). Tomato plants growing in solution culture exhibited a significant reduction in growth when exposed to 28% CO_2 for 24 hours, but were not inhibited by lower concentrations (44). Pea seedlings have been reported to exhibit a significant reduction in growth when exposed to only 1% CO_2 in the root zone (143) whereas barley plants growing in solution culture exhibited no reduction in growth when exposed to 20% CO_2 in the root zone (69). The roots of sour-orange seedlings growing in sand solution culture only ceased growing when exposed to 37.2% CO_2 (62).

Root growth of pea seedling has been reported to be stimulated by exposure to 0.5% CO_2 and inhibited by 1% CO_2 in the substrate (59, 143). The roots that were stimulated by exposure to low CO_2 concentrations were thinner and had an increased amount of lateral root initials. This stimulatory effect of low concentrations of CO_2 was attributed by the authors to the ability of the roots to use CO_2 as a carbon source (59, 116, 143). In light of more recent developments this stimulatory response is probably due to the CO_2 acting as an analogue to ethylene, competing for a receptor site in the cell. This competition would result in a hormonal imbalance that would manifest itself as a more pronounced auxin response (22, 25).

Valmis and Davis (53) investigated the mechanism by which CO_2 damages plant roots and demonstrated differences in sensitivity among plant species to exposure to CO_2 in the root zone. Tomato roots growing in solution culture exposed to pure CO_2 were killed immediately. The exposure of tomato roots under the same conditions to pure nitrogen resulted in a 90% reduction in the rate of growth. Rice plants were also killed by exposure to pure CO_2 in the root zone but exhibited no measurable reduction in rate of growth when exposed to pure nitrogen. Barley plants were killed by exposure to pure CO_2 and exhibited a 45% reduction in the rate of growth when exposed to pure nitrogen. This study shows that high CO_2 concentrations can kill plants by a mechanism other than lack of O_2. Norris et al (108), in 1959 postulated that the damage caused by CO_2 contamination in the root zone occurs when the CO_2 diffuses across the plasma membrane and disrupts the intercellular pH.

To summarize, carbon dioxide concentrations as low or lower than 10% in the root zone can be toxic to roots. Sensitivity of roots to CO_2 is species dependent. Concentrations of 60% or greater have been found to be toxic to all plants so exposed. The mechanism by which CO2 damages plant roots is not known, but the evidence indicates that it is not the same mechanism by which lack of O_2 damages plants.

Effect of Manufactured Gas on Plant Growth

Because it has been extensively studied as a phytotoxic gas when present in soil atmospheres, a review of the literature on the effects of manufactured gas could be enlightening.

The first reported incident of manufactured illuminating-gas damage to trees occurred on Pall Mall, London in 1807 after the first public street light system ever was installed (43). In the late 1800's and early 1900's a number of other researchers found that woody and herbacious plants were damaged by exposure to leaking manufactured-gas (83, 132, 140, 144).

Harvey and Rose (67) in 1915 reported that ethylene was one of the toxic components of manufactured gas. _Catalpa speciosa_, _Ailanthus altissima_, _Vicia faba_, and _Gleditsia_ seedlings were divided into two treatments, one group exposed to illuminating gas and the other to ethylene. The seedlings responded in a similar manner to both treatments. Ethylene concentration in manufactured gas was usually high enough that leaks could be detected by placing tomato plants in the soil and making observations for epinastic curvature the next day (35). It has been shown that ethylene can be generated in concentrations which are biologically active in anaerobic soils (133).

Hitchcock et al (68), in 1934 reported that container-grown willow, cherry, maple and silver bell trees were severely injured when their roots were exposed to manufactured gas for 30 minutes. When cyanogen was removed from illuminating gas, 20 to 24 times more gas was required to cause injury to the trees. Cyanogen forms hydrocyanic acid when mixed with water and carbon dioxide. Cyanogen, as well as ethylene, has been considered to be largely responsible for the phytotoxicity of illuminating gas in soils. These compounds are not found in landfill gases or natural gas in concentrations nearly as high as in manufactured gas, if at all.

Effect of Natural Gas on Plant Growth

The composition of natural gas more closely resembles that of landfill gas than does manufactured gas (Table 1). The main difference between natural gas and landfill gas is that there is more CO_2 and less methane in the latter.

That natural gas can be toxic to plants was first noted by Schollenberger (131) in 1930, who found that plants were killed when the soil was saturated with natural gas, but that no permanent damage to the soil occurred. Exposing the aerial portions of plants to natural gas did not damage the vegetation (136).

Gustafson (65) in 1949 fumigated the roots of container-grown American elm trees during four consecutive growing seasons with concentrations of natural gas not exceeding 4%. Although slight discoloration of the roots was noted on the trees exposed to the gas, no injury to the shoots was reported.

Pirone (115) in 1960 reported that exposing the roots of tomato plants to pure natural gas for 48 hours did not cause any damage. The roots of Norway maples, London plane and pin oaks were fumigated with pure natural gas for 5 to 6 week periods at soil concentrations ranging from 60 to 100%. No damage to the trees was reported due to this treatment.

In 1972, Hoeks (70) reported that natural gas was responsible for the demise of 5 to 20% of the road trees in town centers in the Netherlands. He found that when soil was contaminated with natural gas for a period of time there was a build up of methane-utilizing bacteria whose activity resulted in the depletion of oxygen in the soil. The oxidation of methane follows the general equation ($CH_4 + 2O_2 = CO_2 + 2H_2O$ + Energy). The organisms responsible for this reaction belong to the Pseudomonas and Chromobacteria genera. Under experimental conditions the oxidation of methane was found to be so intensive that if O_2 was in excess all the CH_4 was depleted, and if CH_4 was in excess all the O_2 was utilized. This bacterial activity, in conjunction with simple displacement of the soil atmosphere by natural gas, was concluded by Hoeks to be responsible for the death of the many shade trees in the Netherlands.

Garner (58) in 1973 investigated the death of numerous shade trees near natural gas leaks in Wilmington, North Carolina, and concluded that the death of the trees was due to anaerobic soil conditions brought on by dilution of the soil atmosphere with natural gas and the activity of methane-utilizing bacteria. Garner also partially attributed the death of vegetation to the build up of hydrogen sulfide (H_2S) in the soil produced by Disulfovibrio desulfuricans under anaerobic conditions. He also reported extremely low soil nematode populations due to H_2S toxicity.

THE EFFECT OF SOIL FLOODING ON PLANT GROWTH

Soil saturated with landfill gases (52) or with water (86) often becomes anaerobic. The ability of a plant to survive in anaerobic soil is characteristic of flood tolerant species (61, 158). Such species, therefore, might prove adaptable to adverse growing conditions caused by refuse-generated gases on completed sanitary landfills.

Species vary considerably in their ability to withstand flooding due to a number of biological and environmental factors which are known to influence the ability of a tree species to survive in flooded soil. This is evident in the observable zonation of tree species on river banks, reservoir margins and bottom lands (19, 66, 74). Hardwood species are generally more tolerant of flooding than conifers (1, 61, 92). Soil type can also influence flood tolerance. In the U.S.S.R. on the Volga-Don flood plain Populus alba, P.

balamifera are recommended for clay-loam sites while P. nigra and Acer negundo are recommended for sand-silt sites (151). The time and duration of flooding are important considerations. Dormant trees are less sensitive to flooding than actively growing trees (66). Trees growing on the margins of reservoirs require that the site be flooded no more than 45% of the growing season in order to survive (66). In isolated years some species can tolerate flooding during the entire growing season (60). The condition of the flood water is another factor which may influence flood tolerance. Flooding with standing water is more injurious than flooding with moving water (129). Warm water can accelerate the death of trees exposed to flooding (19). If the flood water covers all or most of the trees above the ground, the tree is more likely to be injured than if only the soil is saturated (66). Older trees are generally more tolerant of flooding. This was found true both for hardwoods (80) and conifers (89).

In order for a species to survive flooding it must possess special characteristics that enable it to survive when the soil is anaerobic. Some species have the ability to undergo anaerobic respiration in the roots when flooded. Species which have been shown to do this are Salix cinerea and Nyssa aquatica (39, 72). The prolonged dependence upon anaerobic respiration can result in a build-up of toxic end products, such as ethanol, which can then become toxic to the plant (57, 76). Hook (72) has postulated that Nyssa aquatica can avoid being damaged in this way by producing secondary roots, thus increasing the size of the root system to compensate for the lack of efficiency and reducing the concentration of ethanol per unit tissue.

A large number of plants possess the ability to transport oxygen to their roots. This characteristic is associated with but not confined to flood-tolerant species. Corn, turnips, barley, carrot, lettuce, beets, leek, pea, onion, rye grass and cabbage (63) all have been shown to transport oxygen to their roots, but none of these species is considered flood-tolerant (72). This adaptation is more common in herbaceous species (61). Woody species, including Populus petrowskyana, Salix alba, S. repens, S. atrocinerea and S. fragilus have also been shown to transport oxygen to the roots. Lenticels on the stem were shown to contribute to this process (7, 27). Other woody species which can transport oxygen to their roots include Fraxinus pennsylvanicum, Nyssa aquatica, N. sylvatica, Avicennia nitida, Picea abies, Liquidambar styraciflua, Liriodendron tulipfera, and Platanus occidentalis (73). Ananas comosus (pineapple) can also transport oxygen to its roots. The gas moving to the roots was observed to contain up to 78% oxygen, most of which was believed to have been produced during photosynthesis (42).

The ability to develop adventitious and secondary roots has also been associated with flood tolerance (60). The original root systems of the flood-tolerant species Fraxinus pennsylvanicum, Platanus occidentalis, and Nyssa aquatica deteriorate when flooded, but secondary roots develop to replace them which are more succulent and less branched (71). Most flood-tolerant species develop adventitious roots at or below the water line (60). The adventitious roots of Salix alba can replace the original root system by growing in the sediment deposited by flood water (119). This could also be true for other species. It has been postulated that adventitious roots in flood water can carry on the salt-absorbing function while the damaged original root system continues to contribute to the water absorbing needs of the tree (85).

The ability to withstand elevated concentrations of CO_2 in the soil has been proposed as contributing to species ability to withstand flooding (72). This possibility has been neglected due to the generally accepted belief that low oxygen and not high CO_2 is the main cause of damage to roots in flooded soils (86). Nyssa aquatica seedlings are more tolerant of flooding and of high CO_2 concentrations in the root zone than Liquidambar straciflua. N. aquatica was not affected by exposure to 2 or 10% CO_2 in the root zone for up to 15 days, whereas 30% CO_2 over the same period retarded root and shoot development and decreased the rate of transpiration. L. styraciflua exhibited chlorosis when exposed to 2% and was killed by exposure to 10 to 30% CO_2 for 15 days (71).

The exact nature of the flood-tolerance mechanism for any species has not been determined. There could be contributing mechanisms other than the ones discussed above. The work done indicates that a combination of adaptations can be responsible for flood tolerance. Nyssa aquatica is tolerant of high CO_2 concentrations in the soil, it can undergo anaerobic respiration, it develops adventitious and secondary roots and it can transport oxygen to the roots. All these adaptations are believed to contribute to its tolerance of flooding (72). The ability of five hardwood trees to tolerate flooding was found to correspond to their ability to transport O_2 to the roots, develop adventitious roots and undergo anaerobic respiration. The more flood tolerant the tree, the more developed were these adaptations. The trees in order of increasing flood tolerance were Liriodendron tulipifera, Liquidambar styraciflua, Platanus occidentalis, Fraxinus pennsylvanica and Nyssa aquatica (71).

The mechanisms which enable a species to adapt to flooding have evolved in response to flooding. The conditions on a sanitary landfill may resemble flooding in terms of anaerobic soil conditions but there are significant differences between the two environments, the most dramatic departure being the lack of water on the landfills. Most flood tolerant species develop adventitious roots which would not be able to develop under landfill conditions due to the lack of water. It is not known to what extent these roots contribute to flood tolerance. It has been postulated that adventitious roots develop in response to a build-up of growth regulators and carbohydrates at the base of the stem and are a response rather than adaptation to flooding (84). Anaerobic soil conditions could be more stable on a landfill than during flooding and not give the trees a chance to grow at all. The ability to withstand high concentrations of CO_2 in the soil might be more important on a landfill where the concentrations of CO_2 in the soil can exceed 40% (52).

EFFECT OF OTHER SOIL PARAMETERS ON PLANT GROWTH

Soil Temperature

A number of investigators have characterized the optimum temperature for root growth of some selected species. As early as the 19th century, King found that corn roots responded quite differently to different soil temperatures throughout the growing season (77). Early in the season, cooler soil temperatures promoted more horizontal root growth than later in the season when higher soil temperatures caused the roots to respond by growing vertically. Burstrom (23) in 1936, found that total growth in length of wheat roots is optimum at temperatures around 68°F and decreases at temperatures above and below this optimum. Richardson (124) described a similar relationship for silver maple (Acer saccharinum). Soil temperatures of 68°F were reported by Rufelt (128) as optimum for maximum growth of wheat plants. The tops of oats generally grow better at 70°F and the roots at 60°F indicating a difference in the optimum temperature for root and shoot growth, respectively.

Total dry weights of both roots and shoots are influenced by the temperature of the root zone. Maximum dry weight of wheat plants increased with decreasing temperatures from 86°F to 50°F, whereas optimum growth of rye grass tops occurred at 67°F with growth decreasing as the temperature was raised to 82°F or lowered to 52°F (107). This same temperature range has been reported for barley (118), rye grass (110), corn, bromegrass (106), oats, tobacco (111), and tomato tops (34). The root growth of wheat and other species was found to be optimum at about 68°F whereas Italian rye grass roots grew best at 52°F (106).

Moisture Stress

Because of their perennial nature, long life, and potentially large size, trees require special consideration in the study of their growth and development under environmental stress. For example, water stresses during several separate growing seasons may affect each year's growth increment and thus, the effect of a given water stress is different in a tree seedling than in a mature tree. Drought during a critical period one year may result in reduced food storage for utilization in growth the following year, and the effect on development of wood tissue or of flowers and fruits can be appreciable for several succeeding years. The root/shoot ratio may be seriously affected by water deficits in woody seedlings, whereas in large trees the more important effect of the same deficits may be in the distribution of growth along the annual sheath of wood.

There is convincing indirect evidence that shoot growth in trees is related to water stress. Forest mensurationists find tree height the most sensitive growth parameter for measuring site productivity, to which the generally accepted key is soil moisture (121, 141, 159). Correlations between rainfall and shoot growth have been attempted with various degrees of success for many decades (102, 113), but there is little doubt that longer shoots are produced in wet years than in dry years by many tree species on upland sites. Root tissues are probably never at as severe water stress as shoot tissue because of the time lag in the build up of water tension between the transpiring leaf and the absorbing root.

Soil water stress reduces the number, rate of expansion, and final size of leaves. In species whose entire leaf crop for one year is present as preformed primordia in the overwintering bud, water stresses of the preceding year regulate the numbers of leaf primordia that form in the developing bud

(40, 81). In these species, e.g. Pinus strobus, water stress during the period of shoot growth has no significant effect on the numbers of leaves that mature, but results in smaller leaves spaced closer together and ultimately less leaf weight (93). Clemments (29) found that numbers of needle fascicles on current shoots of 20-and 5-year old Pinus resinosa were directly proportional to the frequency of irrigation during the previous growing season. Therefore, it can be concluded that the previous year's deficits may affect tree species whose leaf primordia are all preformed in the overwintering bud by reducing leaf numbers, and that current year deficits may reduce the size of leaves and their spacing along the shoots. In other species e.g. Pinus taeda, which can add new foliage throughout the growing season, not all leaf primordia are preformed in overwintering buds, so water deficits during the season of flushing probably reduce production as much as deficits of the previous season (163). Zahner (163) showed that for sapling-size Pinus taeda grown outdoors in large containers, the 2-year effect on elongation of the terminal leader of well-watered trees was almost twice that of trees subjected to extreme drought conditions.

Lotan and Zahner (93) measured elongating needles on 20-year old Pinus resinosa trees under conditions of imposed drought and irrigation. Needles on the irrigated trees expanded for several weeks longer, at a 30% faster rate, and reached a 40% greater length than needles of trees under the drought treatment.

Root growth is also adversely affected by soil moisture stress. Two studies have emphasized that resistance increases sharply as the soil dries, and the resulting physical impedence of penetration by a root tip is considered a limiting factor independent of the deficiency of water for absorption (10, 148). Therefore, the failure of roots to grow into dry soil is probably more the result of physical impedence than of soil water stress. However, cambial growth continues slowly in dry soil because dry soil should not appreciably affect secondary growth (81).

EFFECT OF SOIL PARAMETERS ON SOIL PROPERTIES

Soil Temperature

The processes of ammonification and nitrification in soil are among those affected by soil temperature (128, 157). A temperature between 77°F and 99°F was found to be optimum for the activities of the nitrifying bacteria (147, 156); above 130°F and below 45°F the nitrification rate was severely reduced (156). Ammonification requires a higher optimum temperature (104°F) and the bacteria responsible can remain active at higher temperatures than the nitrifying bacteria. Frederick (55) and Sabey (130) studied nitrification in greenhouse pots of soil without plants. Both corroborated the results of the previous investigators in that higher rates of nitrification were associated with increasing temperatures (from 36°F to 95°F and from 32°F to 86°F, respectively) and that nitrate formation was entirely inhibited at temperatures of 104°F (147, 156).

Low O_2 Tension

Several investigators have found that oxygen concentration in the soil strongly influences the fate of many soil components by altering soil reactions and finally affecting plant growth.

Ponnamperuma (117) has reviewed a large quantity of the literature concerning the dynamics of flooded soils i.e. soils low in oxygen concentration. It is common knowledge that the moment a soil is flooded, its oxygen supply is virtually cut off. Oxygen can enter the soil only by molecular diffusion (which is 10,000 times slower than in the absence of water) (71) or by diffusion of gaseous oxygen through plants from aerial parts through aerenchyma cells continuous with the roots.

When the oxygen supply to the soil is cut off, aerobic organisms quickly deplete the oxygen remaining in the soil and become quiescent or die. The facultative anaerobes, followed by the obligatory anaerobic organisms, then take over the decomposition of soil organic matter; using oxidized soil components such as nitrate, manganic oxides, ferric oxides, sulfate, or phosphate; or dissimilation products of organic matter as electron acceptors in respiration.

Nitrate is the first soil component to undergo extensive reduction when oxygen becomes limited (117). Although it is known that nitrate reduction (denitrification) often occurs in slight amounts in well-aerated soils at optimum moisture level, the percentage of nitrate lost is usually not significant until the oxygen concentration is 12% or lower. A concentration of 0.46% oxygen resulted in comparatively large nitrate losses through denitrification (18).

Almost coincident with denitrification is the reduction of the higher oxides of manganese (MnO_2, Mn_2O_3, Mn_3O_4), because of their similarity to nitrates with respect to redox potential in flooded soils. The reduction may result from these compounds functioning as either (a) electron acceptors in the respiration of microorganisms or (b) chemical oxidants (95). Reduction of the oxidized forms of manganese causes an increase in soluble or manganous-manganese in the soil solution.

The next soil constituent to be reduced in the thermodynamic sequence is $Fe(OH)_2$. This reduction process operates at a considerably lower redox potential than that required for the two previously mentioned compounds (31). The process releases soluble or ferrous iron into the soil solution which can then be taken up by plants or complexed with other molecules.

The reduction of sulfate to sulfide occurs only when the soil has undergone appreciable reduction i.e. when the redox potential has fallen to a very low value (46). However, in soils high in iron, the likelihood of H_2S toxicity to plant roots is minimal because of the formation of insoluble FeS.

ESTABLISHING VEGETATION ON LANDFILLS

Cremer (33), in 1972, planted seedlings of four species of pine in a simulated sanitary landfill wherein raw refuse was placed in steel containers on top of which was placed two feet of soil. After one year the seedlings in these containers were growing as well as the controls.

More, Molze and Browning (101), in 1974, proposed that transpiration by vegetation can reduce the amount of leachate escaping from a landfill. Their study was conducted in a lysimeter designed to simulate landfill conditions. Raw refuse was interspaced with soil in the lysimeter and two feet of soil placed on top. Four woody species were then placed in the lysimeter: silverberry (Elaeganus pungens), black locust (Robinia pseudoacacia), bristly locust (Robinia hispida), and slash pine (Pinus elliottii). All these species grew well in the simulated landfill and were able to reduce the amount of water leached from the modified lysimeters. The roots of the plants grew through the refuse and no methane was reported to have been produced in the lysimeters, indicating that anaerobic conditions did not occur in this simulated sanitary landfill.

Such systems in which small amounts of refuse are placed in containers (lysimeter) do not reproduce true landfill conditions. The small amounts of refuse used cannot duplicate the temperature, gas production or settlement generated by the large quantities of refuse that occur in real landfills.

Swope (146) in 1975, conducted a survey of 24 completed landfills in the state of Pennsylvania. He concluded that 19 of the 24 landfills had vegetative cover inadequate to prevent erosion. Considering only the seeded portions of the nineteen revegetated landfills, twelve were observed to have cover inadequate to prevent erosion. Of five landfills on which no attempts had been made to establish vegetation, four were judged to have a cover of volunteer vegetation inadequate to prevent erosion. The physical soil characteristics most often found limiting to vegetative growth were: low soil fertility, droughtiness, high percentage of course fragments in the soil, slope, and lack of adequate soil cover. The effects of landfill gas contamination of the soil were not examined.

There have been numerous attempts to establish trees and other forms of vegetation on completed sanitary landfills (52). These attempts unfortunately were not designed as controlled experiments. In a national survey, Flower et al (52), examined a number of completed sanitary landfills and reported that problems with the establishment of vegetation included: lack of soil cover, droughty conditions, poor quality cover material, poor planting practices, lack of care, and landfill gas contamination of the soil. In many instances there was a strong direct correlation between the poor growth of vegetation and the occurrence of landfill gases in the soil. Symptoms exhibited by woody species exposed to landfill gas contamination were: a general lack of vigor, dieback, scorching of the leaves or needles, and rapid death. The death of vegetation on or adjacent to landfills caused by landfill gases has also been reported in Japan (152), and Canada (6).

SECTION 5

EXPERIMENTAL PROCEDURES

FIELD STUDIES

Selection of Appropriate Site for Landfill Vegetation Field Study

An ideal site for the species screening and gas-barrier technique study was defined as one which has a relatively high combustible gas concentration and adequate drainage. The control site should be located on virgin land, close to, but not adjacent to the landfill and have no combustible gas in its soil atmosphere. The sites should be large enough to accommodate a four foot spacing between adjacent trees.

An appropriate site for the experiment was located on the tidal marsh of the Raritan River in East Brunswick, New Jersey a distance of about two miles from the Cook Campus (Figure 1). The site had been operated as a landfill since the early-1960's by the Herbert Sand Company which offered space on the landfill and space on a nearby undisturbed tract of land for the experimental and control plots respectively.

Adjacent to the southern boundary of the landfill is a woodlot. This was an island used as a defensive position by colonial forces during the Revolution. All other landfill boundaries are tidal creeks that flow into the Raritan River or other landfills located over marshland.

The geologic history of this area is Atlantic Coastal Plain with the Piedmont Plateau boundary less than one mile to the North and West. According to Patrick et al (112), the soil would be sassafras loam or sandy loam with a sand deposit that is quarried on the southern side of the woodlot. The soil covering the landfill seems to be a sassafras subsoil as indicated by the presence of quartz and other stones with a reddish-yellow to yellow-brown tint (149).

Characterization of Vegetation on Edgeboro Landfill

In order to evaluate the degree of change imposed on the area by our experimental plantings, we first characterized volunteer vegetation in the area. For the most part the work in surveying the native vegetation was accomplished with a minimum of equipment (36). The mapping was performed by use of a hand-held compass, and the distances were measured by pacing on the landfill and by the use of a wheeled odometer on the woodlot. The bearings and distances measured were placed on graph paper to show the respective outlines of the two areas studied. Plotting the map on graph paper helped in determining the area by the formula using a coordinate system.

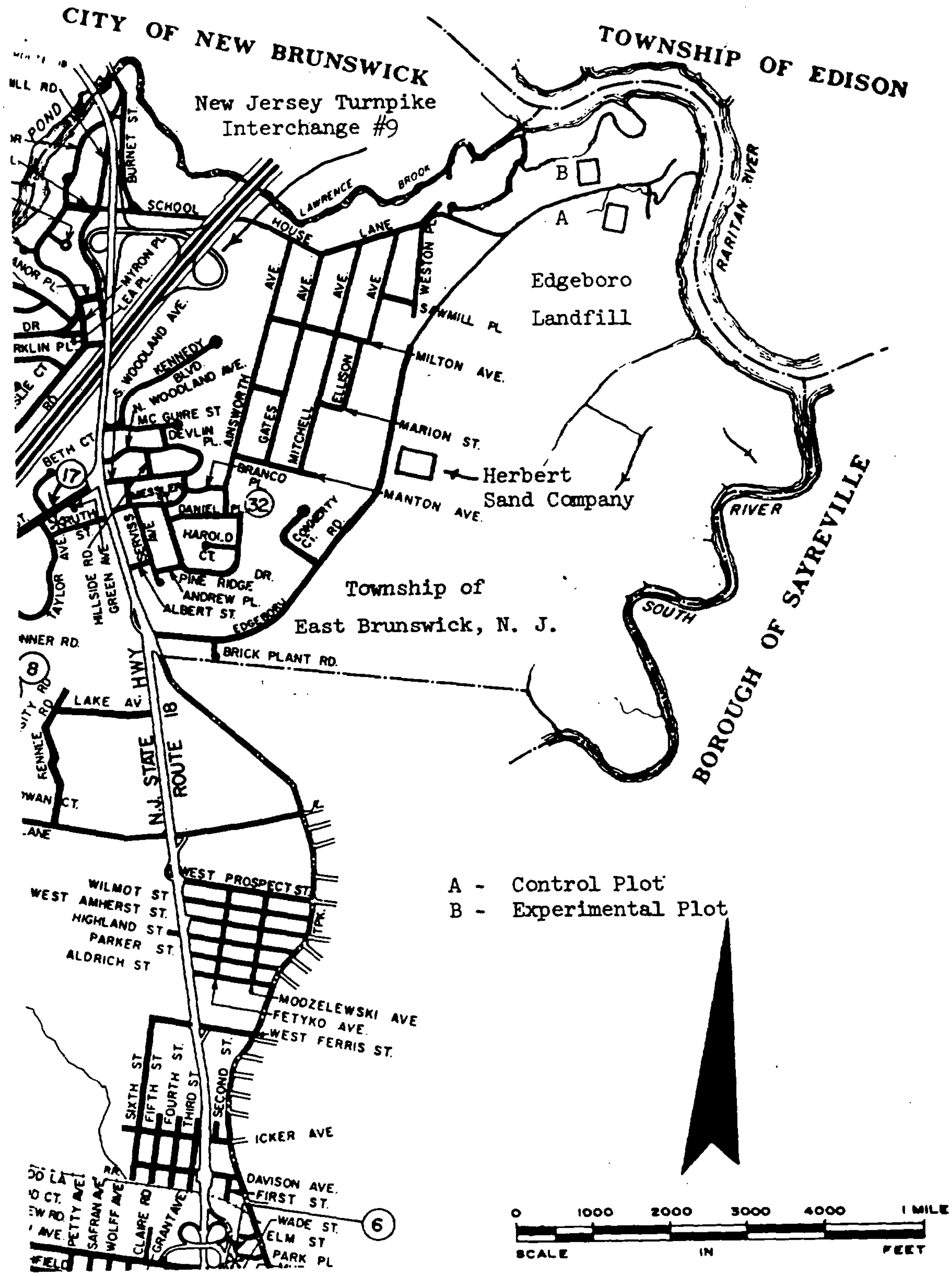


Figure 1. Location of landfill vegetation growth experiment, East Brunswick, New Jersey

$$2(\text{Area}) = Y_a(X_b - X_n) + Y_b(X_c - X_a) + \ldots\ Y_n(X_a - X_{n-1})\ (104).$$

Twenty-five randomly stratified plots, 50x50 feet, were used to determine the composition and successional changes in the woodlot (Figure 2). In each plot, the DBH (diameter at breast height, $4\frac{1}{2}$ feet) of all trees over two and one-half inches was recorded with the use of a 24-inch tree caliper. In the case of one sassafras tree a metric biltmore stick graduated at two centimeter intervals was used and the result converted to the English system. The shrub layer was measured by the number of stems in a plot.

On the landfill, stems of all woody species were counted since only three trees were above the minimum stem DBH of two and one-half inches. As a check to note the effectiveness of the woodlot as a seed source, the number of stems on each side of the road dividing the landfill approximately in half from the southwest corner to the northeast corner was determined.

Unfilled Island Vegetation--

The island was divided into nine different regions that are at varying stages of succession or are dominated by a defined cover type (Figure 2).

1) Grass and rose stage - Here the dominant species are *Andropogon virginicus*, *Phragmites australis* and *Rosa spp*. Over most of the area *Andropogon* is dominant except where the moisture seems to collect, and here *Phragmites* will tend to be dominant. Different species of wild roses come up through these grasses and tend to prepare the soil for the next stage of development.

2) Bayberry-smooth sumac stage - The roses give way to a thick shrub cover of bayberry (*Myrica pensylvanica*) and smooth sumac (*Rhus glabra*). Seedlings of black cherry (*Prunus serotina*) and black gum (*Nyssa sylvatica*) appear through this canopy starting the succession toward a forest cover type. Arrowwood viburnum (*Viburnum dentatum*) acts as an understory to both sumac and bayberry, but eventually replaces the latter as the dominant shrub while the former attempts to become the canopy species.

3) Smooth sumac-black cherry-sassafras stage - A tree canopy becomes established with sumac and cherry predominating and sassafras (*Sassafras albidium*) advancing as a challenger for the dominant position. Smooth sumac has to be considered a tree species here since it reaches 20 feet in height and a maximum of $5\frac{1}{2}$ inches DBH. Black gum is co-dominant to the other three species while the major understory species is flowering dogwood (*Cornus florida*). Bayberry is still present in the shrub layer, but is losing fast to the Arrowwood viburnum under a closed canopy. A small number of red maple (*Acer rubrum*) are associated, but never become more than an associated co-dominant species.

4) Black cherry-sassafras-black gum stage - This stage is more or less the same as the previous stage, but smooth sumac has dropped out from competition and oak-hickory regeneration has started. The shrub layer is dominated by arrowwood and the understory by flowering dogwood. After this stage the succession will go to oak-hickory or to sassafras if it can regenerate

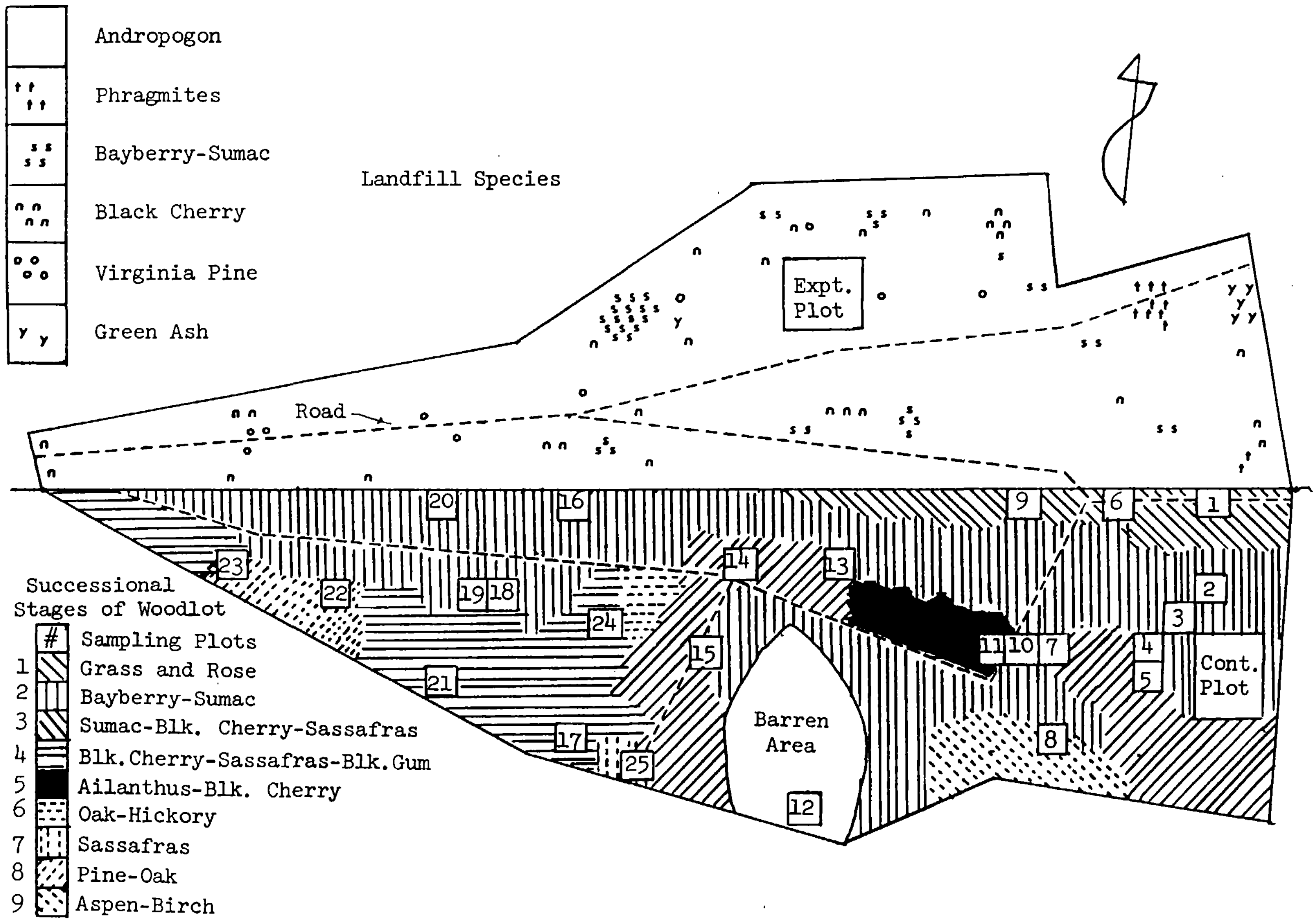


Figure 2. Species distribution on landfill and successional stages on adjoining woodlot.

vigorously.

5) Ailanthus-black cherry stage - Ailanthus (Ailanthus altissima) replaced smooth sumac earlier in the succession and becomes the dominant species with black cherry co-dominating. The succession seems to follow the same sequence as from stage 3), the only exception being that Ailanthus will take longer to succumb to the more tolerant species so that oak-hickory regeneration will occur while it is still present in the canopy.

6) Oak-hickory stage - This type resembles Type 40 (Post Oak-Black Oak) of the Society of American Foresters (54). Black oak (Quercus velutina) and bitternut hickory (Carya cordiformis) are the dominate canopy trees with black gum, post oak (Quercus stellata), sassafras and black cherry in the co-dominate position.

7) Sassafras stage - An allelopathic substance from the leaves of sassafras inhibits the regeneration of other species and a stand is produced that will be mono-species in content for a long part of its life. The regeneration of sassafras under its own canopy is slow to non-existent in older stands. The stand in the woodlot has the largest tree present, 33 inches DBH, plus two others over 20 inches DBH. This is S.A.F. Type 64 (54).

8) Pine-oak stage - This is a Society of American Foresters (S.A.F.) Type 76 (54) with Virginia pine (Pinus virginiana) dominant with advance oak regeneration of post oak, black oak, blackjack oak (Quercus marilandica), and pin oak (Quercus palustris) as the rising co-dominant species (97). Red maple is associated with this cover type and would seem to take a secondary position with black gum to the species mentioned above.

9) Aspen-birch stage - Although this is an earlier transition form, it is not the dominate form on the north side of the woodlot. On the south side this quaking aspen-grey birch variation of S.A.F. Type 19 (54) has a much higher coverage. Quaking aspen (Populus tremuloides) and grey birch (Betula populifolia) form the dominate cover of this area with a shrub layer changing from bayberry to arrowwood. The associated species are black gum and Malus spp., the latter is either a domestic apple or one of the types of wild crabapples.

Landfill Vegetation--

The landfill itself is still too early in succession to designate a forest cover type or one that may be emerging, so three areas of examination were conducted: the ground cover, the shrub layer and the arborescent vegetation that is developing.

1) Ground cover - This is very similar to stage one in the woodlot, Andropogon is predominant with Phragmites localized. Trailing strawberry (Euonymus obvatus) and greenbriar (Smilax rotundifolia) crisscross the open areas with the former being the only live vegetation over the gas upwellings when it sends a stolon from one side of the gas area to the other.

2) Shrub layer - Bayberry and smooth sumac are the predominant shrubs, forming pure patches in localized areas scattered over the landfill. Not as

numerous, but still present are the wild roses and the Malus spp. found as scattered bushes over the area. Found now in greater numbers or for the first time, are the black haw (Viburnum prunifolium), highbush blueberry (Vaccinium corymbossa) and witch hazel (Hamamelis virginiana), probably from the Raritan River Flood Plain, which represents another seed source influencing the landfill site. These occur as scattered bushes for the most part.

3a) Arborescent vegetation, north side - Black cherry is very numerous, being about six times as numerous as ailanthus, black gum, and red maple. Lesser amounts of pin oak, sweet gum (Liquid-ambar styraciflua), boxelder (Acer negundo), green ash (Fraxinus pennsylvanica), and cottonwood (Populus deltoides), again probably from the flood plain, were found with the usual old-field species grey birch, eastern redcedar (Juniperus virginiana), shortleaf pine, sassafras, and black locust (Robinia pseudoacacia). Most of the tree forms occur on the edge of the landfill where there is probably more soil and less refuse. Absence of any gas upwelling seems to be responsible for the growth of most, if not all, these trees.

3b) Aborescent vegetation, south side - The area here is greater than that on the north side of the road, but the vegetation is sparser. The numbers of black cherry are about one-third less than on the other side, but it is still the most numerous species found. A small grove of green ash is found on the northeastern corner of this section, near a patch of Phragmites, numbering about two-thirds the amount of black cherry found here. Associated with the green ash are boxelder, and honeylocust (Gleditsia triacanthos), again species found on river bottoms. The rest of the species found in reducing frequency are eastern redcedar, grey birch, red maple, sassafras, ailanthus, shortleaf pine, black gum, and quaking aspen, all of which are found in the woodlot.

Discussion--

At first the flood plain was not considered a major seed source, but because of the prevailing winds from the northwest and the large numbers of birds and rodents from the flood plain visiting the landfill, a reversal in thinking occurred after the data were collected. The prevailing winds work against the woodlot as a source of windblown seed as shown by the low number of shortleaf pine seedlings. The seedlings of pine found on the landfill showed a distribution pattern emanating from the southwest. When the winds are from this direction they blow through the pine stand. The flood plain is then the major source of wind-blown seeds while probably equal to the woodlot as a source of animal-borne seeds.

The presence of two seed sources will show a different trend than that seen in the woodlot. This greater number of species may be an added benefit since a greater variety of responses of more trees can be seen than if there were but one seed source.

Any trend now seen on the landfill would be superficial, since major root competition is just beginning to occur in the soil. The soil depth varies on the landfill from the edges where more soil is usually found to the areas of gas upwellings that have been eroded by the wind to expose the refuse. Billings (13) states that Virginia pine has most (56-64%) of its root system in the top 6 inches of soil, while oaks and other more tolerant species tend to have deeper root systems. The distribution of roots into the deeper portions of soil increases with time over the life of the stand. The next ten to twenty years will be the true test of this natural vegetation to see whether the roots do penetrate the refuse or if the refuse acts as a barrier and prevents penetration. The result may then be an edaphic climax or a constant shifting of types until no gas exists in the soil. Roots often have the habit when possible, to circumvent a barrier and send roots to areas more favorable, as shown by Stout (145). One Virginia pine in particular, found growing on the landfill was checked for the presence of mycorrhizal fungi after a basidiocarp was found adjacent to it. The fungus was not identified, but the pattern of the tree roots was striking. A lateral root from the sapling grew out of the north side of the tree and swung clockwise around the tree until it found a path to a better soil condition marked by increased vegetation. On the eastern and western sides of the tree, areas of gas upwelling were found. A second pine in a similar situation had very poor form and vigor, and a check of the roots showed an absence of mycorrhizal fungi and a compact root system.

Final Evaluation--

Vegetation succession on the landfill is still in the very early stages of tree growth (9, 100). Patterns are not occurring too far out of sequence even though the number of trees may be high for the age of abandonment (eleven years). A study of the patterns of root growth of these trees could be quite useful in understanding the problems that occur in establishing plantings on landfills. Coupled with these observations mycorrhizal fungi could be evaluated for their help in relieving vegetation stresses that occur here. Table 1 summarizes the main species found on the Edgeboro Landfill site and adjacent island.

TABLE 1. TREE DISTRIBUTION AND DENSITY - EDGEBORO LANDFILL AND ISLAND

Species	Number Found On Landfill North Section	South Section	Also Present In Woodlot	Test Plot
Acer rubrum	15	3	X	X
Acer negundo	1	2	-	-
Ailanthus altissima	17	2	X	-
Betula populifolia	7	3	X	-
Fraxinus pennsylvanica	3	19	-	X
Gleditsia triacanthos	0	2	-	X
Hamamelis virginiana	0	1	-	-
Juniperus virginiana	3	9	X	-
Liquidambar styraciflua	3	0	-	X
Malus spp.	3	4	X	-
Myrica pensylvanica	40	115	X	X
Nyssa sylvatica	16	1	X	X
Pinus echinata	9	1	X	Genus
Populus deltoides	1	0	-	"

(continued)

TABLE 1. (continued)

Species	Number Found On Landfill North Section	Number Found On Landfill South Section	Also Present In Woodlot	Also Present In Test Plot
Populus tremuloides	0	1	X	Genus
Prunus serotina	86	30	X	-
Quercus palustris	4	0	X	X
Rhus glabra	340	282	X	-
Robinia pseudoacacia	5	0	X	-
Rosa spp.	38	16	X	-
Sassafras albidium	3	3	X	-
Vaccinium corymbosa	18	19	X	-
Viburnum prunifolium	38	5	X	-

Total Area

Woodlot = 463,150 square feet = 10.63 acres
Landfill = 442,700 square feet = 10.16 acres
X = presence
- = not found
Genus = different species of same genus found

Site Conditions

The refuse in the Edgeboro landfill ranges in depth from 20 to 35 feet and consists primarily of municipal refuse plus some light industrial waste. The areas on the landfill where these data were collected were completed between 1966 and 1969. There is a foot or less of final soil cover over the refuse. No attempts have been made to vegetate this landfill; therefore, all vegetation observed growing on it consists of volunteer native species.

Ten permanent stations were established on the landfill where vegetation was either growing very well or not at all (Figures 3 and 4, Table 2). Acrylic gas sampling devices (Figure 5) designed to enable extraction of a micro-sample of the soil atmosphere for gas chromatographic analysis were buried at a depth of 10 inches at each of these stations.

The depth of cover material at the permanent stations was determined by digging five holes with a spade. Each approximately 18-inch diameter hole was dug until the refuse was reached. Then a yardstick resting on undisturbed soil was placed across the top of the hole. A second yardstick was used to measure the distance from the top of the cover. This distance was recorded as the depth of cover.

The soil atmosphere was analyzed by two methods, one utilizing a macrosample, one a microsample:

1) The macrosample was obtained by means of the MSA model 2A Explosimeter and Fyrite O_2 and CO_2 analyzers. The O_2, and CO_2, and combustible gas readings were all taken from separate holes within 1 foot of

each other when taken at the same station.

2) A microsample was obtained by first extracting a 5 ml. gas sample through the sampling device (Figure 5) with a syringe and discarding it. After extracting this volume, the tygon tubing was pinched to prevent a back flow of ambient air. A 0.5 ml. sample was then extracted through the sampling device with a gas-tight syringe and the sample sealed in the syringe by inserting the needle into a rubber stopper. The sample was then analyzed in a Carle model 8500 gas chromatograph equipped with a porpack Q and molecular sieve column system and a thermal conductivity detector.

The gas chromatograph was calibrated with standard gas concentrations supplied by Matheson Gas Products of East Rutherford, New Jersey. A flow of gas was established through a soft rubber tube, one end of which was attached to the regulator on the standard gas cylinder and the other end immersed in water to prevent a back flow of ambient air. A gas-tight syringe was then used to extract a 0.5 ml. sample through the tubing and inject it into the chromatograph. The recorder attached to the chromatograph was equipped with an intergration unit which translates the area under the gas peaks into standard units which were then plotted against the known concentrations of the gas to produce standard curves. The calibration procedure was performed once a month. Once a week a standard gas concentration was passed through the chromatograph to insure accuracy of the calibration curves.

TABLE 2. DESCRIPTION OF PERMANENT STATIONS ON THE COMPLETED SANITARY LANDFILL

Station	Description
A.	Oval area approximately 50 feet long by 38 feet wide. No vegetation growing in this area.
B.	Kidney shaped area about 500 feet long by 25 feet wide. Very little vegetation-only a few scattered clumps of brome grass covering less than 5% of the surface area.
C.	Circular area approximately 25 feet in diameter. At the center was a pin oak tree 15 feet high with a DBH of 8 cm. Moss was observed growing under the oak and brome grass grew all around it. The vegetation in this area provided 100% cover.
D.	Round clump of staghorn sumac about 15 feet in diameter. The sumac was about 6 feet high at the center. It appeared healthy, exhibiting good growth this season. Also in this area was a 10 foot high sweet gum tree with a DBH of 4.5 cm. It also exhibited good growth this season. The soil in this area tended to be very wet.
E.	Oval area approximately 20 feet long by 10 feet wide. Brome grass was growing in this area in sparse clumps providing about 25%

(continued)

TABLE 2. (continued)

Station	Description
	cover. This was the only poorly vegetated station where vegetation appeared to be increasing its percent coverage during the course of this study.
F.	Irregularly shaped 10 feet diameter group of staghorn sumac and peach trees. The sumac was 4.5 feet tall. It did not exhibit good growth this year. There were two peach trees, one about 4 feet high and one 6 feet high, which appeared healthy. The larger exhibited a good production of fruit in 1977.
G.	Round area about 25 feet in diameter. No vegetation was observed growing here.
H.	Round area about 25 feet in diameter. There was a good cover of brome grass and weeds in this area, providing close to 100% cover.
I.	Round area about 15 feet in diameter. A small group of peach trees about 6 feet high. These trees exhibited poor growth this year. There was also a 6-foot-tall crab apple tree with a DBH of 4 cm. that appeared healthy and grew well this year. There was a considerable amount of refuse on the surface in this area. Newspapers found in the refuse were dated January, 1969.
J.	Oval area approximately 18 feet long by 10 feet wide. The vegetation in this area provided less than 5% cover. It consisted of a few scattered clumps of brome grass and one chlorotic staghorn sumac 10 inches high. There was a considerable amount of refuse on the surface in this area. A newspaper found in the refuse was dated November, 1968.
K.	Irregular area approximately 15 feet in diameter. There was a healthy stand of peach trees here about 7 feet tall which grew very well in 1977.

Preparing The Experimental And Control Field Plots

Two field experiments were designed; one to screen tree species for adaptability to landfill conditions and the second to test gas-barrier systems for effectiveness in preventing contamination of root zones by landfill gases.

Species Screening Experiment--

One foot of sandy subsoil was spread over the entire experimental screening area followed by 8-10 inches of topsoil. Because there were two or three inches of original soil cover over the refuse prior to construction, this brought the total cover to approximately 2 feet.

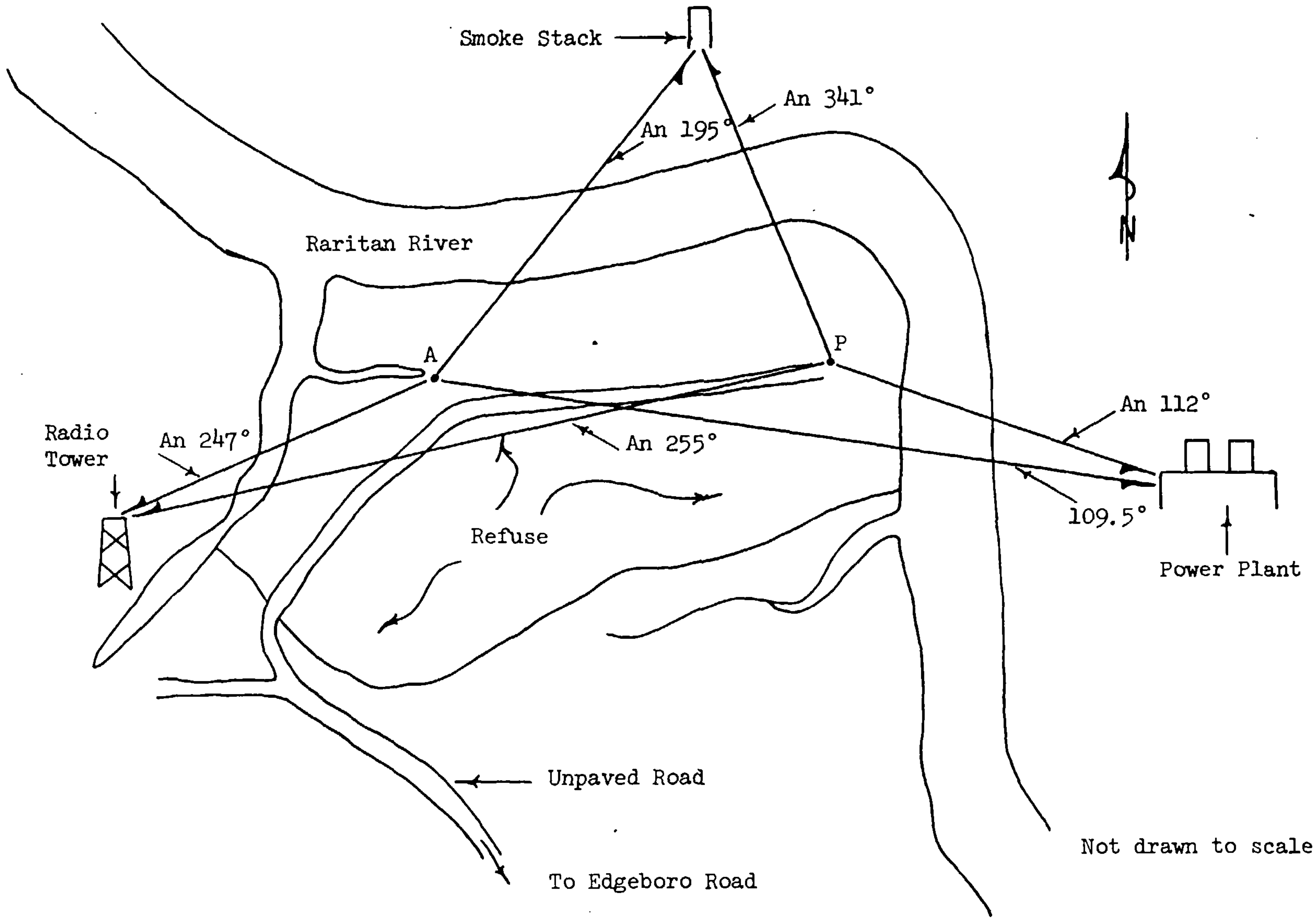
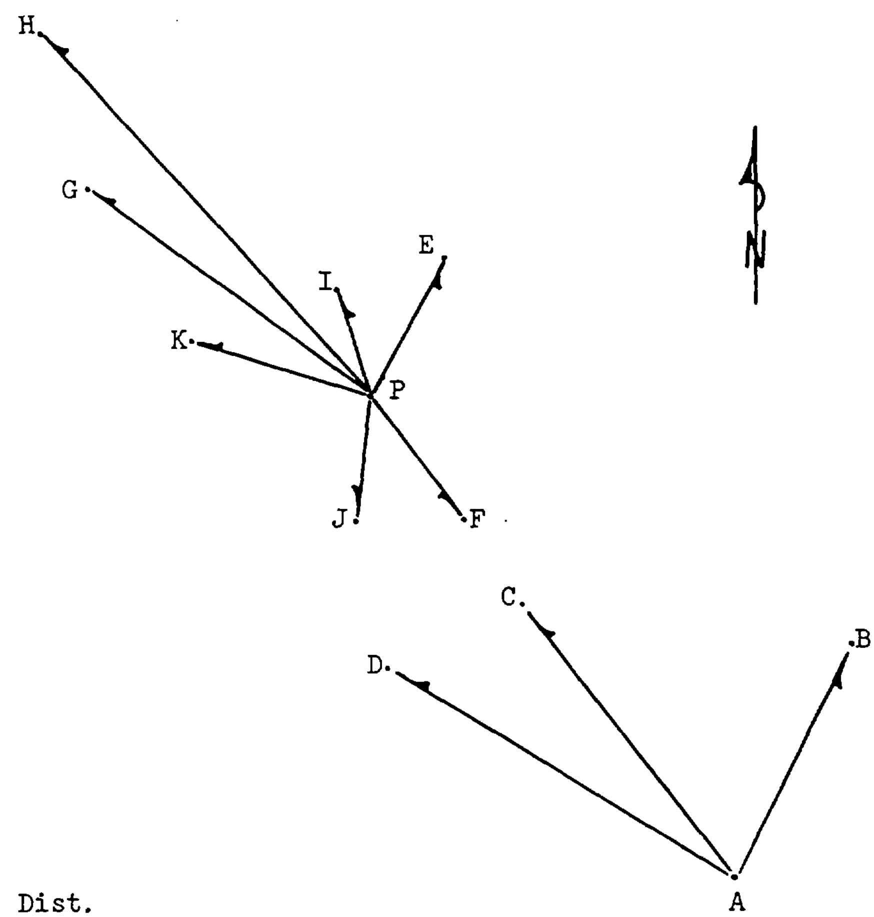


Figure 3. Edgeboro Sanitary Landfill, East Brunswick, New Jersey, location of reference stations for gas and vegetation sampling points.



From	To	Dist. (in feet)	An°
A	B	180	22
A	C	235	320
A	D	265	299
P	E	40	26
P	F	42	140
P	G	157	312
P	H	220	315
P	I	25	343
P	J	37	186
P	K	7	303

Figure 4. Gas and vegetation sampling points on Edgeboro Sanitary Landfill.

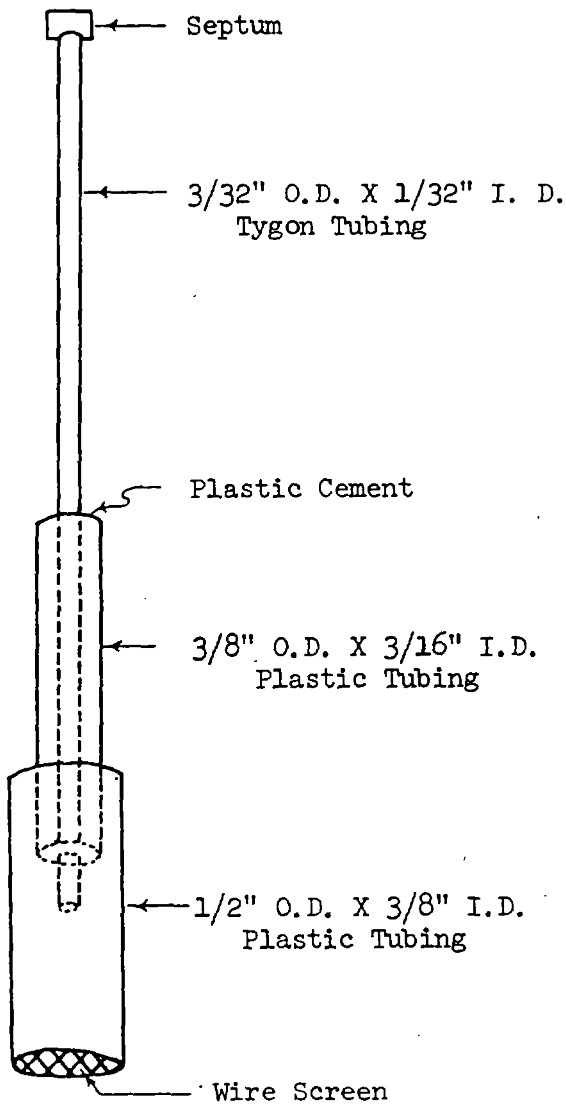


Figure 5. Plastic soil gas sampler.

Following removal of the native vegetation, one foot of the same sandy subsoil spread on the experimental landfill plot was deposited on top of the control area. Eight to twelve inches of topsoil were then placed on top of the subsoil. The topsoil layer was about 2 inches deeper here than in the experimental plot. This was due to the need for extra soil to fill in the tracks created by the large tractor used to level the area.

Combustible gas readings were taken by means of the MSA Model 2A Explosimeter over much of the site at 50 foot intervals until a large enough area with high combustible gas concentrations was found.

The experimental plot measures 72'x108', an area large enough to accommodate ten replicates of nineteen different tree and shrub species and five landfill gas-barrier systems (Figure 6). The control is located approximately a quarter-mile from the experimental plot and is on a former undisturbed woodland. It measures 46'x110' and accommodates ten replicates of the same nineteen species planted on the experimental plot, in addition to two gas-barrier systems (Figure 7).

The experimental landfill plot is exposed to strong winds and driving rains, as is typical of many of the larger landfills. The control plot, located on the north side of an adjacent wooded rise, is only moderately exposed on the south and southwest where native woodlands remain. These native woods comprise sassafras, red oak, mockernut hickory, red maple and dogwood, species typical of a young forest community which normally follows 20-30 years after a disturbance such as a fire or clear cut.

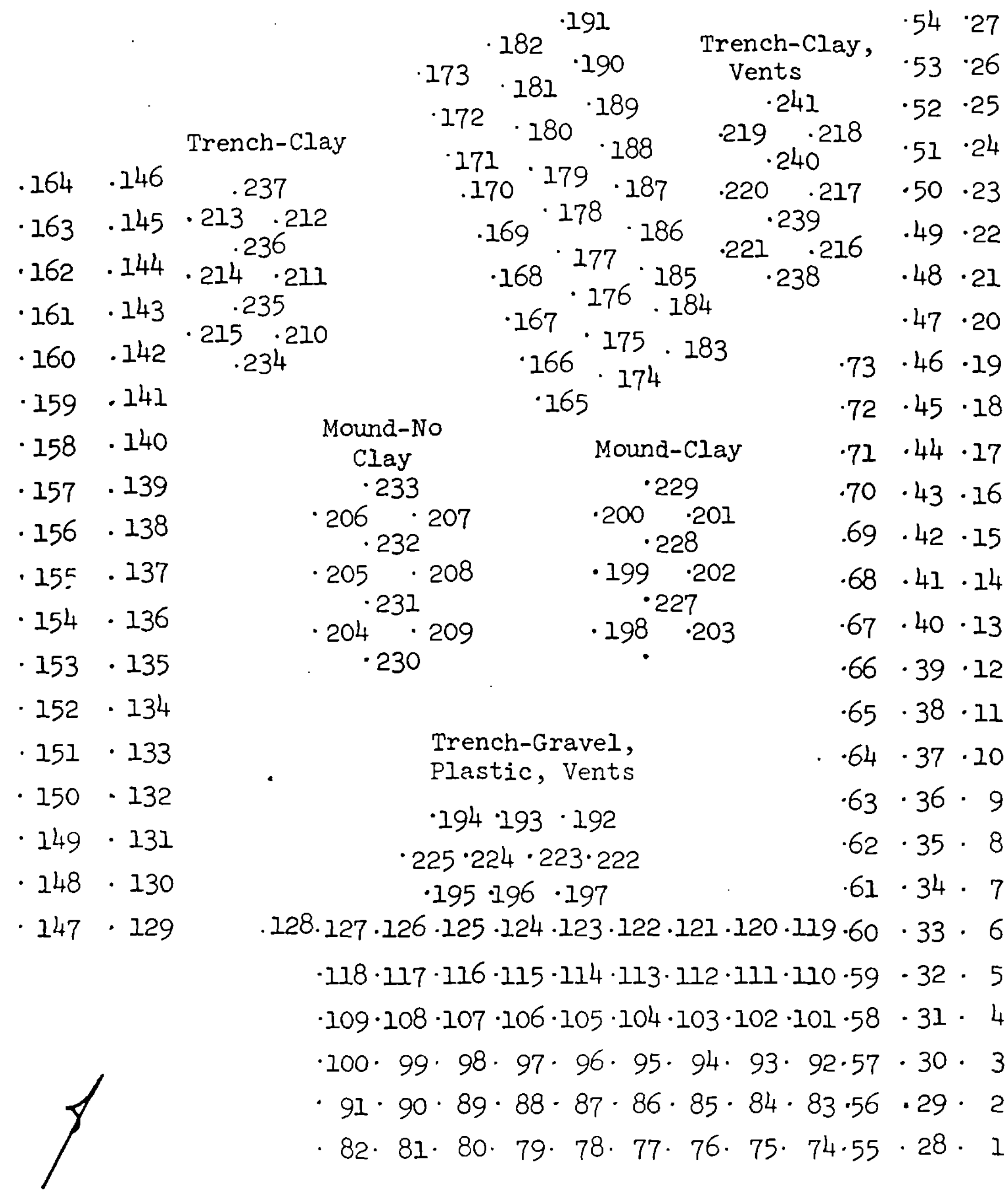
Drainage on both the experimental and control plots is good and should not be a limiting factor for tree growth.

Gas-Barrier Techniques--

Following the designation of the experimental plot, the precise boundaries for three 10'x14' trenches and two 14'x18' mounds were determined by selecting the areas of highest combustible gas concentration in the soil atmosphere. A caterpillar tractor bulldozer was used to dig the three 3 foot deep trenches and to move the excavated rubbish from the experimental site.

In order to prevent landfill decomposition gases from penetrating the soil, the three trenches were lined at the bottom with various barrier materials prior to backfilling with topsoil. One of the two mounds was underlain with a barrier whereas no barrier was used in the second mound.

Plastic/gravel/vents trench--This trench (Figure 8) was lined with a one-foot layer of 1 inch round road gravel which was deposited on the trench bottom by means of a front-end loader and spread out evenly with a hand rake. Two plastic gas samplers were buried in the gravel to permit the analysis of accumulated gas. Ten holes were then dug in the gravel around the periphery of the trench into which were placed ten 5-foot long, 4-inch diameter perforated polyvinyl chloride pipes. The perforations are $\frac{1}{2}$ inch in diameter and are orientated at 90° angles at 6 inch intervals. A 16'x12' sheet of 4 mil polyethylene plastic was cut to fit over the PVC pipes and placed on



Legend: Numbers identify specific trees
Trees spaced 4' apart

Figure 6. Location of trees on species screening area and gas-barrier techniques on experimental plot.

Mound

.210
.202 .199
.209
.201 .198
.208
.200 .197
.207

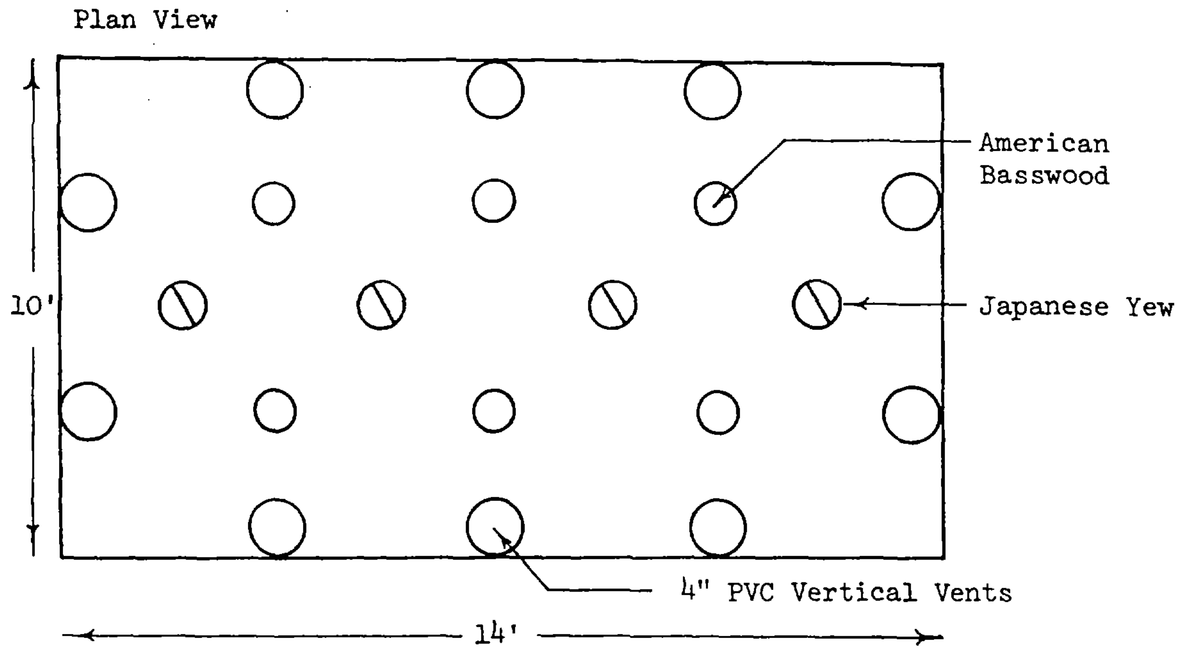
Trench

.206
.194 .193
.205
.195 .192
.204
.196 .191
.203

	175	150	125	100	75	50	25
	174	149	124	99	74	49	24
	173	148	123	98	73	48	23
	172	147	122	97	72	47	22
	171	146	121	96	71	46	21
	170	145	120	95	70	45	20
	169	144	119	94	69	44	19
	168	143	118	93	68	43	18
	167	142	117	92	67	42	17
	166	141	116	91	66	41	16
190	165	140	115	90	65	40	15
189	164	139	114	89	64	39	14
188	163	138	113	88	63	38	13
187	162	137	112	87	62	37	12
186	161	136	111	86	61	36	11
185	160	135	110	85	60	35	10
184	159	134	109	84	59	34	9
183	158	133	108	83	58	33	8
182	157	132	107	82	57	32	7
181	156	131	106	81	56	31	6
180	155	130	105	80	55	30	5
179	154	129	104	79	54	29	4
178	153	128	103	78	53	28	3
177	152	127	102	77	52	27	2
176	151	126	101	76	51	26	1

Legend: Numbers identify specific trees
Trees spaced 4' apart

Figure 7. Location of trees on species screening area and gas-barrier techniques on control plot.



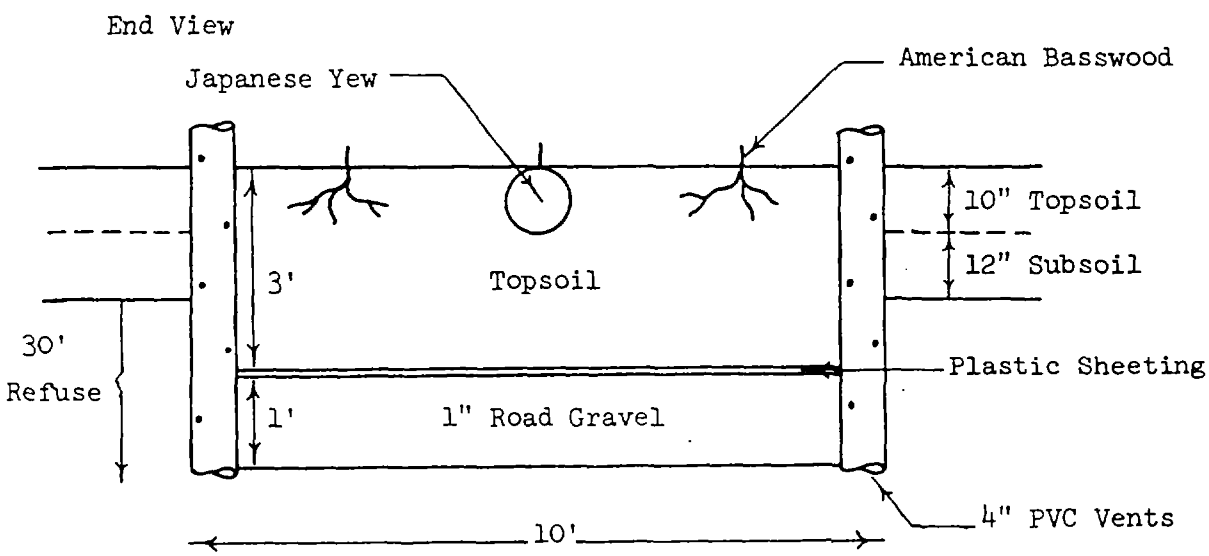


Figure 8. Design of gravel/plastic/vents trench.

top of the road gravel. Presumably this made a seal through which no decomposition gas could migrate. It was expected that the gas collected under the plastic sheeting would be carried to the soil surface via the perforated pipes, thereby bypassing the 3-feet of topsoil backfilled into the trench. The tops of the ten perforated pipes extend approximately 1 foot above the soil surface.

Clay/vents trench--This trench (Figure 9) was lined at the bottom with a one-foot layer of clay similar to that used in California to exclude decomposition gases. The clay was obtained from virgin land about one-half mile away and brought to the site via a large earthscraper tractor. A front-end loader was then used to deposit the clay on the trench bottom. Some of the clay was friable and could be easily spread by hand shovel; however, a large portion of it had to be broken into smaller pieces to allow for better compaction. After the clay was adequately spread, it was packed down tightly by foot. Ten ventilation pipes, similar to those used in Figure 8, were placed vertically around the periphery of the clay bed, hopefully, to remove the gases of landfill decomposition prior to their entering the trench. Finally the trench was filled with 3-feet of topsoil.

Clay/no vents trench--This trench (Figure 10) was lined at the bottom with a foot-thick clay layer as was the previous trench. However, this trench has no perforated pipes for venting landfill gas. After the clay was spread and compacted, 3-feet of topsoil were backfilled into the trench.

Two experimental mounds were also constructed for preventing gas migration.

No clay mound--This mound (Figure 11) was constructed of the same quality topsoil as that used in the trenches. The final mound dimensions were 14'x18' at the base, 8'x12' at the top, and 3' in height with 45° sloping sides.

Clay barrier mound--To keep the landfill gases out of the root zone, this mound (Figure 12) (same dimensions as the previous mound) was underlain with a one-foot layer of the same type clay as used in trench-clay/vents and trench-clay. The clay base below the mound has an overall dimension of 16'x20' thereby extending one foot beyond the base of the mound.

The control plot contained one trench and one mound constructed to the same dimensions as those on the experimental plot with topsoil similar to that used on the experimental plot. No gas barriers or vents are associated with the trench or mound in the control plot.

Selection of Experimental Species

In order to test species representative of a maximum number of desirable landscaping characteristics and a variety of genotypes, plants were chosen from the following categories: deciduous shrubs, deciduous trees, needle-leaf evergreens and a broad-leaf evergreen. Within these categories, species were selected for: 1) tolerance to low oxygen tension environments; 2) tolerance to city conditions; 3) aesthetic landscaping purposes; 4) ubiquity; 5)

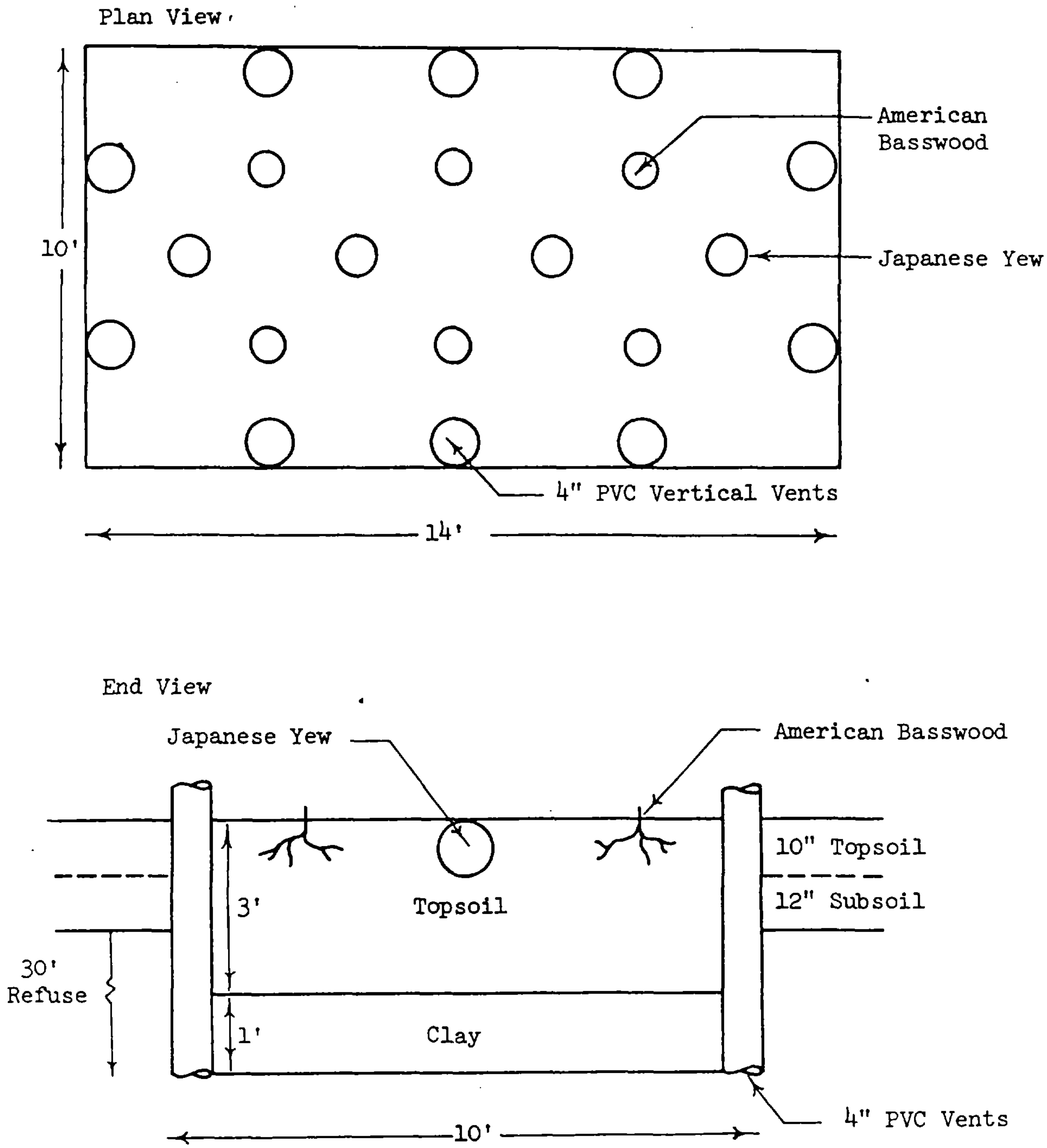


Figure 9. Design of clay/vents trench.

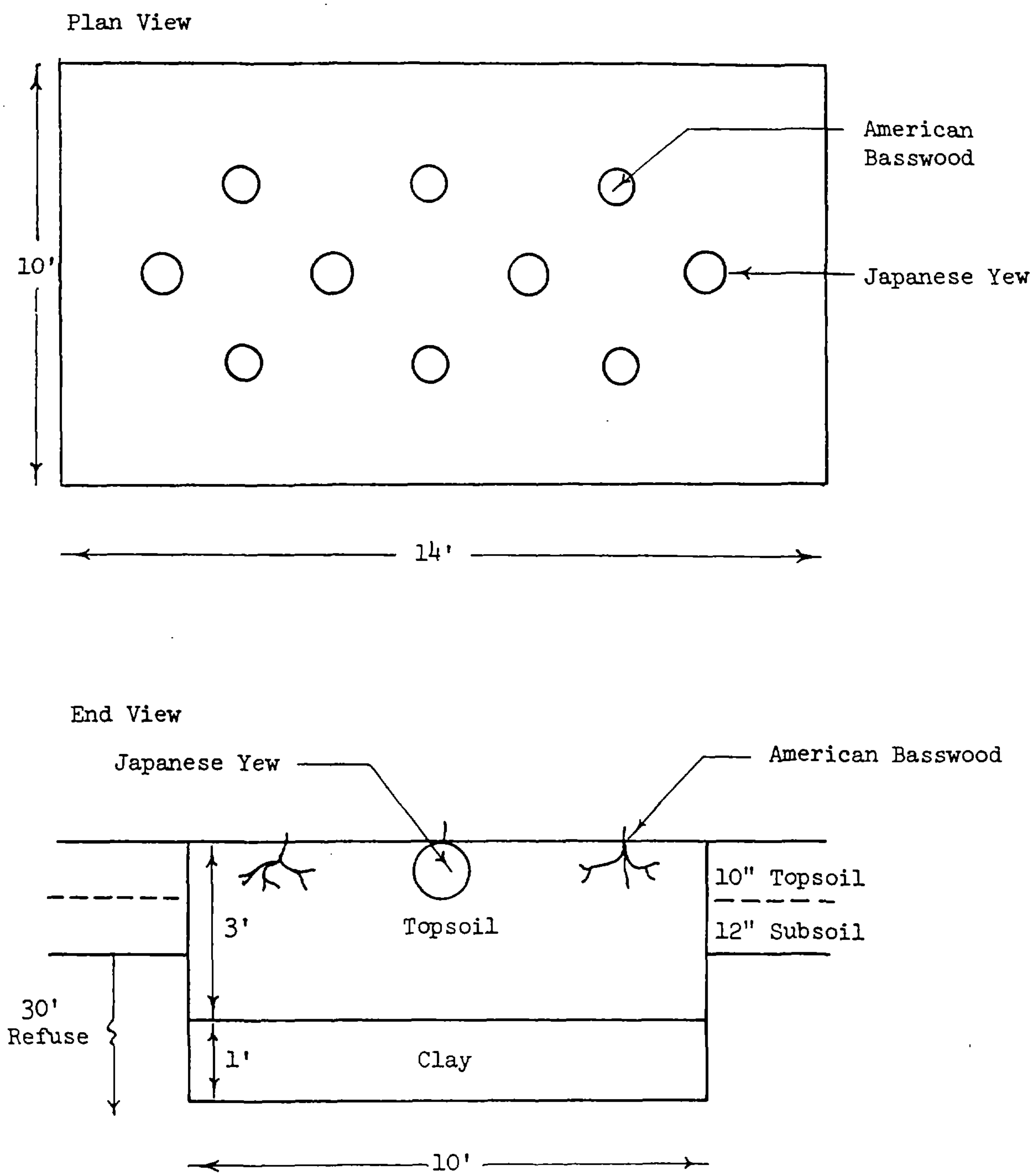


Figure 10. Design of clay/no vents trench.

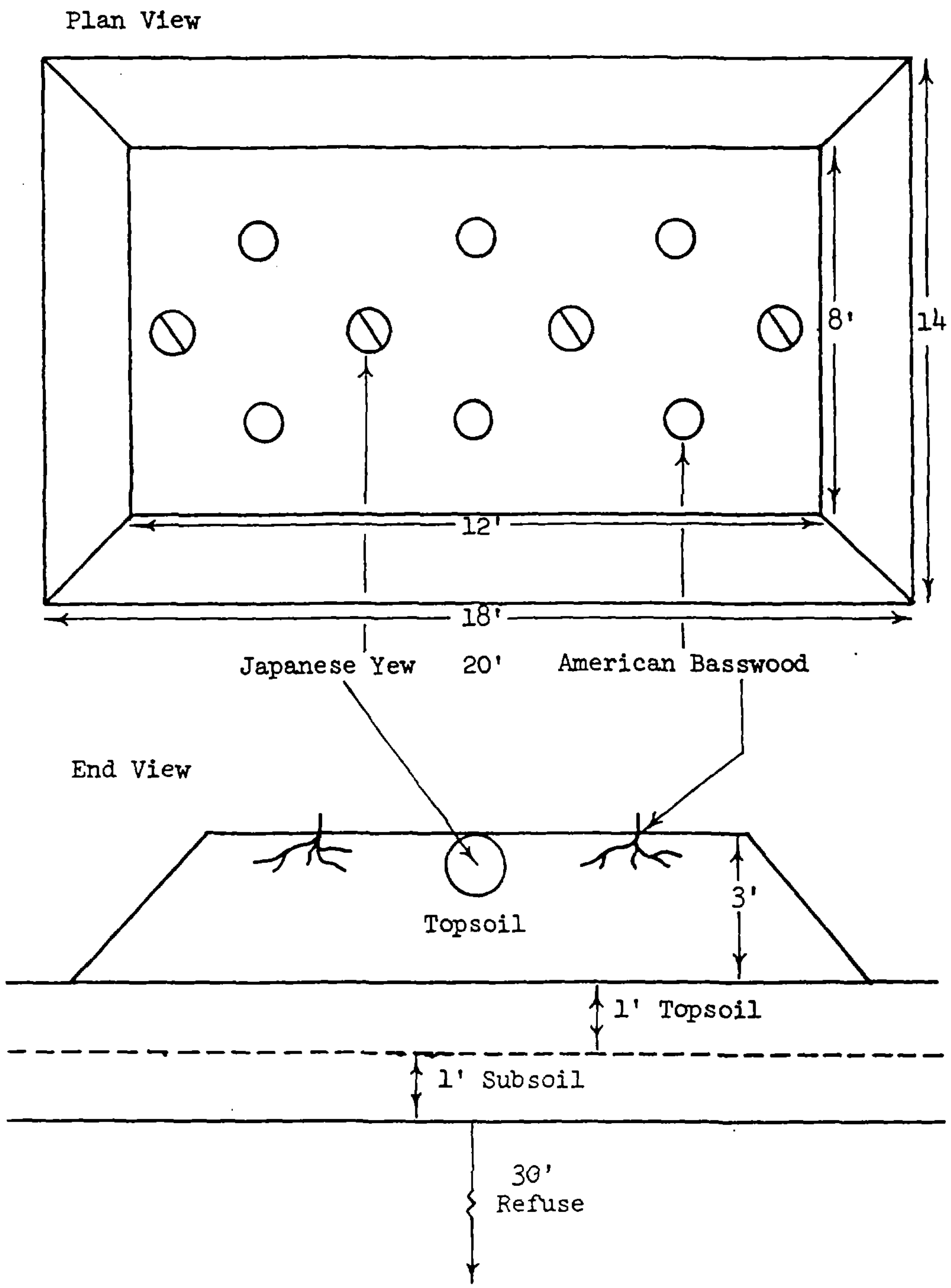


Figure 11. Design of no clay-barrier mound.

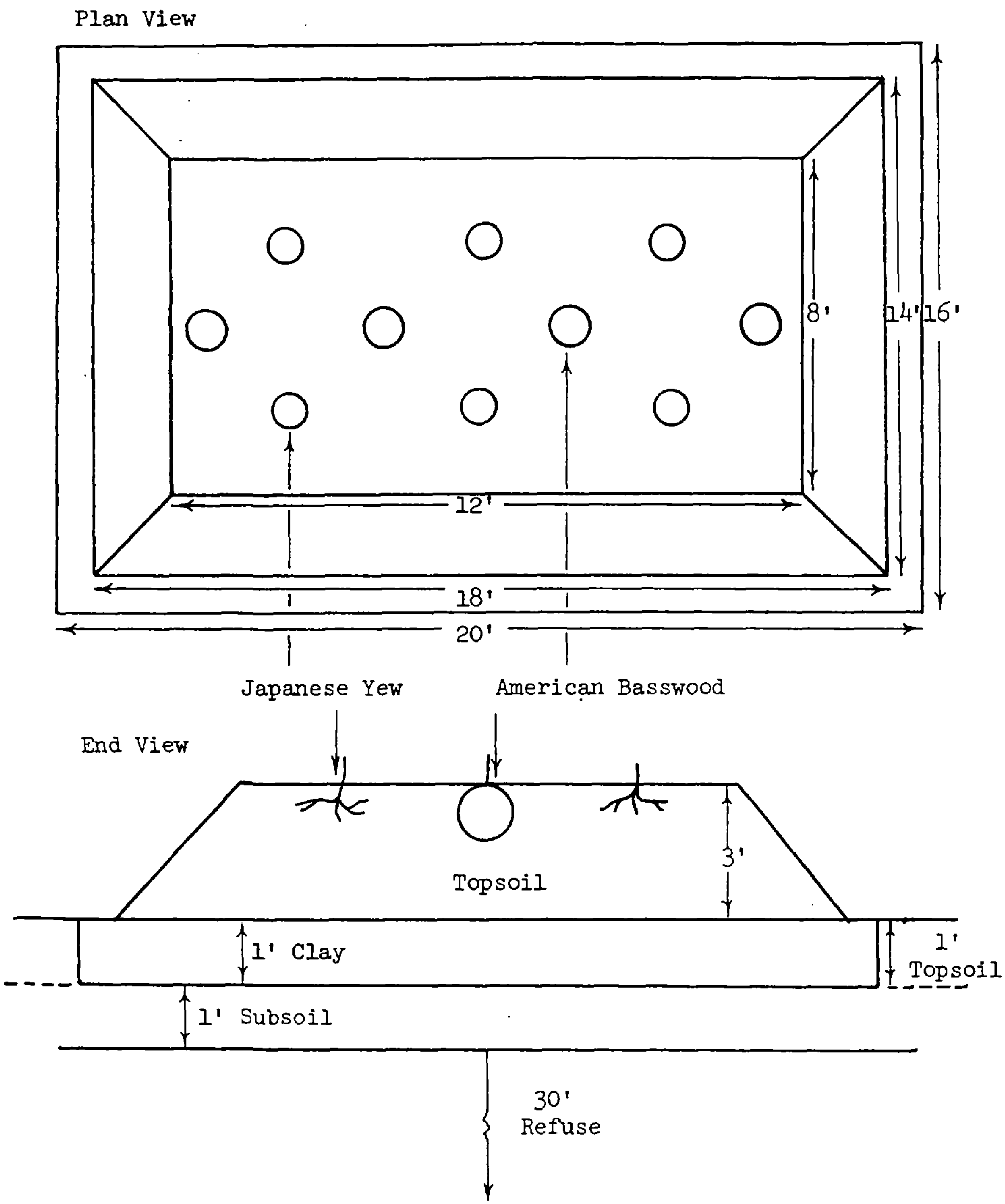


Figure 12. Design of clay-barrier mound.

susceptibility to natural and landfill gas injury; 6) tolerance to sea salt; 7) ease in transplanting; 8) minimal costs (Table 3).

Nineteen species (Table 4) were selected according to the above eight criteria. American basswood and Japanese yew were chosen for planting on the trenches and mounds because of their reported susceptibility to landfill gases. All species chosen for the experiment were judged to be relatively easily transplanted and obtainable at local commercial nurseries at a reasonable cost.

Planting of Trees and Shrubs

The trees were spaced at 4 foot intervals to allow for several years of growth uninhibited by adjacent trees. For random placement of the trees, points were marked in rows on the plot to accommodate all the trees. These points were assigned numbers in consecutive order on both plots from 1 to 210 and 1 to 240 (Tables 5a & 5b) (Figures 6 & 7) for the control plot and experimental plot respectively. For each species, ten of these numbers were selected from a random numbers table, and the ten replicates were planted in locations bearing these numbers on the dates shown in Table 6.

The planting holes were dug by means of a pick and shovel. Those for bare-rooted trees were dug deep enough to accommodate the vertical expanse of the root system and 3 to 6 inches wider than the lateral expanse. The balled and burlapped trees and the trees in containers were planted in holes as deep as the root ball or container and about 12 inches wider in diameter. The holes extended down into the sandy subsoil in the majority of cases.

As the trees were placed in the holes, the topsoil was backfilled to three-fourths of the original hole depth. The soil was packed firmly by foot and watered. When the water had been absorbed, the remainder of the hole was filled with topsoil and loosely packed by hand. A 2-inch ridge was constructed around each tree to act as a catch-basin.

Because of the loss of roots when the trees were dug at the nursery, the bare-rooted trees required branch pruning. This was done after the trees had been planted. Thirty to fifty percent of most of the viable branches was removed as well as all dead tissue.

The large deciduous trees were staked in order to stabilize them in the soil and prevent windthrow. Two 2"x2"x6' Douglas fir stakes were driven into the soil on either side of each tree perpendicular to the direction of the strongest prevailing winds. Plastic chain-lock was used to secure the tree between the two stakes.

Cultural Methods

Fertilizing--

In 1976, soil nutrient analyses for both the experimental and control plots indicated low nitrogen, phosphorus and potassium levels. In order to bring these nutrients to a medium level in the soil, on April 16-17, 1977, four pounds of 10:10:10 granular fertilizer were spread around each tree on

TABLE 3. TREE PLANTING SELECTION CRITERIA

	Trees	Tolerance to Low O_2 Tension Environments	Ubiquity	Aesthetic Landscaping Purposes	Sea Salt Tolerance	Tolerance to City Conditions	Susceptibility to Landfill Gases
DECIDUOUS TREES	Honey Locust			X			
	American Sycamore	X		X		X	
	Red Maple	X	X	X			
	Green Ash	X		X			
	Black Gum	X		X			
	Black Willow	X		X			
	Pin Oak	X		X			
	Ginkgo			X		X	
	Sweet Gum			X			
	American Basswood			X			X
	Hybrid Poplar			X			
	Mixed Hybrid Poplar			X			
DECIDUOUS SHRUBS	Euonymus			X			
	Bayberry	X		X			
BROADLEAF EVERGREEN SHRUB	Rhododendron			X			
NEEDLE LEAF EVERGREENS	White Pine			X			
	Japanese Black Pine			X	X		
	Norway Spruce			X			
	Japanese Yew			X			X

TABLE 4. SPECIES SELECTED FOR VEGETATION GROWTH EXPERIMENT AT EDGEBORO LANDFILL

Abbreviation	Latin Name	Common Name	Selection Criteria*
Ar	Acer rubrum	Red Maple	1,2,3
Ea	Euonymus alatus	Euonymus	3
Fl	Fraxinus lanceolata	Green Ash	1,3
G	Ginkgo	Ginkgo	3,5
Gt	Gleditsia triacanthos	Honey Locust	1,3
Ls	Liquidambar styraciflua	Sweet Gum	3
Mp	Myrica pensylvanica	Bayberry	1,3
Ns	Nyssa sylvatica	Black Gum	1,3
P	Populus	Poplar (Hybrid)	3
Pe	Picea excelsa	Norway Spruce	3
Pm	Populus m	Poplar (Mixed Hybrid)	3
Po	Plantanus occidentalis	American Sycamore	1,3,5
Ps	Pinus strobus	White Pine	3
Pt	Pinus thunbergi	Black Pine	3,4
Qp	Quercus palustris	Pin Oak	1,3
R	Rhododendron Roseum elegans	Rhododendron	3
Sb	Salix babylonica	Weeping Willow	1,3
Ta	Tilia americana	American Basswood	3,6
Tcc	Taxus cuspidata capitata	Japanese Yew	3,6

* Selection Criteria

1. Tolerant of low O_2 environments
2. Ubiquity
3. Aesthetic landscaping purposes
4. Sea salt tolerance
5. Tolerant to city conditions
6. Susceptibility to landfill gases

TABLE 5a. PLANT KEY FOR EDGEBORO LANDFILL TREE GROWING EXPERIMENT FOR THE CONTROL PLOT

Tree Number	Latin Abbreviation	Tree Number	Latin Abbreviation	Tree Number	Latin Abbreviation	Tree Number	Latin Abbreviation	Tree Number	Latin Abbreviation
1	Ea	39	Ls	77	Qp	115	Ea	153	Sb
2	Tcc	40	Pm	78	Sb	116	R	154	R
3	Fl	41	Ar	79	Tcc	117	Ar	155	G
4	Ta	42	Pm	80	Pe	118	G	156	Ea
5	Fl	43	P	81	Qp	119	Ls	157	Fl
6	Ea	44	Pe	82	Pm	120	Mp	158	Gt
7	Po	45	P	83	Tcc	121	Pm	159	Fl
8	Qp	46	Ps	84	Gt	122	Ar	160	Ar
9	Tcc	47	Ns	85	Fl	123	Ls	161	Mp
10	Po	48	Pm	86	Ta	124	Qp	162	Ns
11	Ar	49	R	87	R	125	Ea	163	Ph
12	P	50	Ph	88	Ps	126	Ea	164	Gt
13	G	51	Ta	89	Pe	127	Ps	165	Pe
14	Ps	52	Gt	90	Sb	128	Pt	166	Ea
15	Po	53	Ls	91	Ns	129	Fl	167	Fl
16	P	54	Tcc	92	Sb	130	Qp	168	Gt
17	Ls	55	Sb	93	Ps	131	Ps	169	Ta
18	Tcc	56	Mp	94	Ea	132	Gt	170	Pm
19	Ta	57	Pm	95	Gt	133	Ta	171	G
20	Qp	58	Ta	96	R	134	Ea	172	Qp
21	Mp	59	Po	97	Tcc	135	Ph	173	Ls
22	Sb	60	Pt	98	Ar	136	Mp	174	Pm
23	Fl	61	G	99	Ta	137	Ns	175	Pt
24	Ls	62	Qp	100	Pe	138	Pe	176	Pe
25	Pe	63	Ns	101	Ph	139	Fl	177	Tcc
26	Ns	64	Gt	102	Ls	140	G	178	Ls
27	Sb	65	Gt	103	G	141	Tcc	179	Ps
28	G	66	Pm	104	Ar	142	Po	180	Pe
29	Pt	67	Ps	105	Ns	143	Qp	181	Ta
30	R	68	Po	106	Pt	144	Ph	182	Mp
31	Ps	69	Pt	107	Ps	145	R	183	Mp
32	G	70	Ro	108	Sb	146	Po	184	Pt
33	Qp	71	Po	109	Pt	147	Ar	185	Ta
34	Mp	72	Ar	110	Pe	148	R	186	Mp
35	Sb	73	Ls	111	Pt	149	Po	187	Pt
36	Ea	74	Fl	112	Pm	150	G	188	Ns
37	Ar	75	R	113	Mp	151	Gt	189	Ns
38	Sb	76	Ns	114	Po	152	Ph	190	Tcc
								191 - 202	Ta
								203 - 210	Tcc

* See Table 4 for key to abbreviations

TABLE 5b. PLANT KEY FOR EDGEBORO LANDFILL TREE GROWING EXPERIMENT FOR EXPERIMENTAL PLOT

Tree Number	Latin Abbreviation								
1 -	Pm	39 -	Ls	77 -	Ns	115 -	Fl	153 -	G
2 -	Tcc	40 -	Sb	78 -	Qp	116 -	Ns	154 -	Gt
3 -	Po	41 -	Pm	79 -	Ta	117 -	Ps	155 -	P
4 -	Ta	42 -	Ea	80 -	Sb	118 -	Ar	156 -	Sb
5 -	Po	43 -	Pm	81 -	Pe	119 -	Ls	157 -	G
6 -	Ea	44 -	P	82 -	Qp	120 -	G	158 -	Sb
7 -	Fl	45 -	Pe	83 -	Pm	121 -	Gt	159 -	Tcc
8 -	Qp	46 -	P	84 -	Po	122 -	Ea	160 -	Po
9 -	Ea	47 -	Ps	85 -	Gt	123 -	Pt	161 -	Gt
10 -	Fl	48 -	Ns	86 -	Po	124 -	Ls	162 -	Ea
11 -	Ar	49 -	R	87 -	Ta	125 -	Tcc	163 -	Po
12 -	P	50 -	Ta	88 -	R	126 -	Ea	164 -	Pt
13 -	G	51 -	P	89 -	Mp	127 -	Sb	165 -	Ar
14 -	Ps	52 -	Ta	90 -	Pe	128 -	Ps	166 -	Pt
15 -	Fl	53 -	Gt	91 -	Sb	129 -	Pt	167 -	Ns
16 -	Fl	54 -	Mp	92 -	Ar	130 -	Po	168 -	Po
17 -	Ls	55 -	Ls	93 -	Pt	131 -	Qp	169 -	Gt
18 -	P	56 -	Ar	94 -	Ps	132 -	Ps	170 -	P
19 -	Ta	57 -	Ps	95 -	Sb	133 -	Gt	171 -	Tcc
20 -	Qp	58 -	Mp	96 -	Mp	134 -	Ta	172 -	Ns
21 -	Mp	59 -	Pm	97 -	R	135 -	Tcc	173 -	Ea
22 -	Tcc	60 -	Ta	98 -	Ps	136 -	P	174 -	Pe
23 -	Po	61 -	Fl	99 -	Ar	137 -	Mp	175 -	Gt
24 -	Ls	62 -	Pt	100 -	Ea	138 -	Ns	176 -	Ta
25 -	Pe	63 -	G	101 -	Pe	139 -	Pe	177 -	Pm
26 -	Ns	64 -	Qp	102 -	P	140 -	Fl	178 -	G
27 -	Ta	65 -	Ar	103 -	Ls	141 -	G	179 -	Qp
28 -	Sb	66 -	Gt	104 -	G	142 -	Pm	180 -	Ls
29 -	G	67 -	Gt	105 -	Ar	143 -	Po	181 -	Pt
30 -	Pt	68 -	Pm	106 -	Ns	144 -	Qp	182 -	Mp
31 -	R	69 -	Ar	107 -	Pt	145 -	Ea	183 -	Pm
32 -	Ps	70 -	Tcc	108 -	R	146 -	Mp	184 -	Pt
33 -	G	71 -	R	109 -	Sb	147 -	P	185 -	Tcc
34 -	Qp	72 -	Fl	110 -	Ea	148 -	R	186 -	R
35 -	Mp	73 -	Pt	111 -	Pe	149 -	Fl	187 -	Sb
36 -	Tcc	74 -	Ls	112 -	Mp	150 -	Ar	188 -	Ps
37 -	Pe	75 -	Tcc	113 -	Pm	151 -	R	189 -	Pe
38 -	Ns	76 -	R	114 -	Qp	152 -	Fl	190 -	Ls
								191 -	Ns
								192 - 221 -	Ta
								222 - 241 -	Tcc

* See Table 4 for key to abbreviations

TABLE 6. TREE AND SHRUB PLANTING DATA

Screening Experiment	Dates of Planting: Site A (Control Plot)	Dates of Planting: Site B (Experimental) Plot	Approximate Tree Height at Planting
Honey locust (a)*	4-22-76	4-4-76	7'-8'
American sycamore (a)	4-27-76	4-6-76	10'-12'
Red maple (a)	4-22-76	4-4-76	6'-8'
Green ash (a)	4-22-76	4-6-76	10'-12'
Black gum (c)	4-15-76	4-9-76	3'-4' (8" cans)
Weeping willow (a)	4-27-76	4-15-76	14'-15'
Norway spruce (b)	4-14-76	4-8-76	18"-24"
White pine (b)	4-15-76	4-8-76	18"-24"
Euonymus (b)	4-27-76	4-27-76	15"-18"
Bayberry (b)	4-10-76	4-9-76	12"-15"
Pin oak (a)	4-27-76	4-4-76	6'-8'
Rhododendron (c)	4-15-76	4-6-76	12"-18" (6" cans)
Ginkgo (a)	4-22-76	4-4-76	5'-6'
Japanese black pine (b)	4-10-76	4-8-76	18"-24"
Japanese yew (b)	4-27-76	4-8-76	18"-24"
Sweet gum (c)	4-26-76	4-26-76	3'-4' (8" cans)
American basswood (a)	4-22-76	4-23-76	7'-8'
Hybrid poplar (a)	4-6-76	4-3-76	9'-10'
Mixed hybrid poplar (a)	4-15-76	4-3-76	1'
Barrier System Experiment			
Basswood - trenches	4-23-76	4-23-76	7'-8'
Basswood - mounds	4-23-76	4-23-76	7'-8'
Yew - trenches	6-10-76	6-10-76	18"-24"
Yew - mounds	6-10-76	6-10-76	18"-24"

* Shipping Method:

(a) Bare-rooted
(b) Balled and burlapped
(c) Containerized

both plots for a total of 840 pounds with a standard granular fertilizer-spreader.

Liming--

Both plots were limed with pulverized dolomitic-limestone on April 18, 1977. In order to raise the pH to 6.5, forty-six lbs./1000 square feet were applied to the control plot and fifty-seven lbs./1000 square feet to the experimental plot by means of a standard walk-behind spreader.

Irrigation--

The rainfall in New Brunswick in the early spring of 1976 and 1977 was enough to maintain the soil at a moisture level sufficient for adequate tree growth, but by the middle of May in both years, the soil moisture* had reached a low enough level to warrant irrigation. During the summer of 1976, a one-horsepower irrigation pump with a 3/4 inch outlet hose was used to allocate water to each tree. The water was pumped from a series of four 55-gallon drums located in the back of a pick-up truck. Approximately three gallons were applied to each tree at each irrigation period at a rate of 200 gal./hour. This method of irrigation was quite time-consuming and provided only a limited amount of water for each tree.

On July 10, 1977 an alternative method of irrigation was made available. A 2000-gallon fuel-oil truck was converted into a water-supply truck by the Herbert Sand and Gravel Company and arrangements were made to utilize this truck for irrigating the trees. Approximately ten gallons were now applied to each tree at each watering at a rate of 2000 gal./hour. When the weekly rainfall was inadequate, the plots were irrigated on the weekend by this more efficient method which allocated more water/tree in a shorter period of time.

Pest Control--

On July 7, 1976, the following tree species were sprayed with liquid Sevin: pin oak, American sycamore, green ash, red maple, ginkgo, American basswood, hybrid poplar, and mixed hybrid poplar for the control of gypsy moth, tent caterpillars and canker worms which were already present on some of the experimental trees and on many of the surrounding trees growing naturally on the landfill. A second spray was applied on July 18, 1976 for the same insect species.

On May 6, 1977, the following tree species were sprayed with liquid Sevin for the control of tent caterpillars and canker worms which were present on some trees: particularly the pin oaks, American basswoods, weeping willow and hybrid poplar.

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*Soil moisture was tested by the squeeze method, i.e. when a handful of soil was squeezed and water dripped from the soil, it was classified as wet; when no water came out but the soil stayed together in a clump the soil was moist; and when the soil crumbled after squeezing, the soil was considered dry and the plants were irrigated.

Rodent Control--

On December 29, 1977, a $\frac{1}{2}$ inch mesh screen supported by three stakes was placed around each euonymus shrub to prevent damage by rabbits.

Plot Maintenance--

During the growing season, grass and weeds were periodically cut with a power mower and weeds were pulled from the area immediately surrounding each tree trunk. Tree support-stakes were driven back into the ground when loosened and the plastic chain-lock supporting trees between stakes was replaced when necessary.

Sampling Methods

Soil Gas Analyses--

During the summer of 1976, combustible gas was measured in situ by means of a Mine Safety Appliance Model 2A Explosimeter. A $\frac{1}{2}$ inch hole was punched in the soil to the desired depth by means of a commercial bar-hole maker. The sample was withdrawn from the bar-hole by use of a 3-foot long nonsparking probe. A rubber stopper was placed over the upper end of the sampling probe to help seal the bar-hole from the ambient air. The Wheatstone bridge principle is used within the instrument for determining the concentration of combustible gases.

Gas data were taken at a 1-foot soil depth from eleven collection points on the experimental plot and eight points on the control plot on 7/7/76 and 9/13/76. Gas data were also collected from the trenches and mounds of the gas-barrier technique experiments on these same dates. Measurements were made at the 1-foot soil depth at six points within each gas-barrier technique and at four or six points around the periphery of the trenches, as well as within the vent pipes.

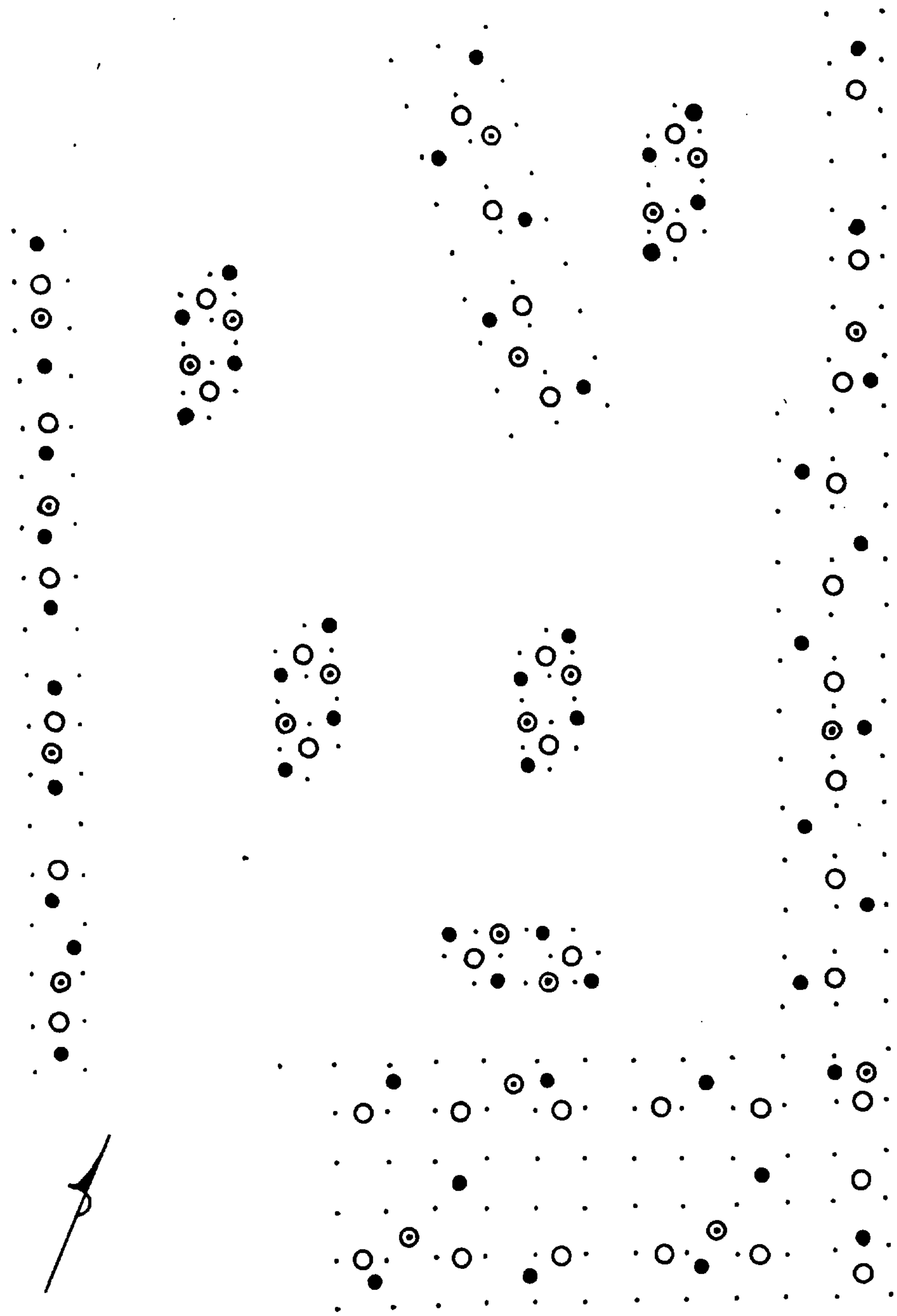
During 1977, gas samples were collected from forty-eight buried samplers approximately every two weeks, beginning in March and ending in August, when all plants had ceased growing. Forty-two of the sampling stations were on the experimental plot (Figure 13) and six on the control plot (Figure 14). The device in Figure 5 was used for obtaining the soil gas samples. In the experimental screening area, one sampler is in place for each group of six plants, whereas in the trenches and mounds, there is a sample for each group of five plants.

Soil Temperature Analyses--

Soil temperatures at the 1-foot depth were collected at the same sample points (Figure 13 & 14) and on the same dates as the gas samples.

Soil Moisture Analyses--

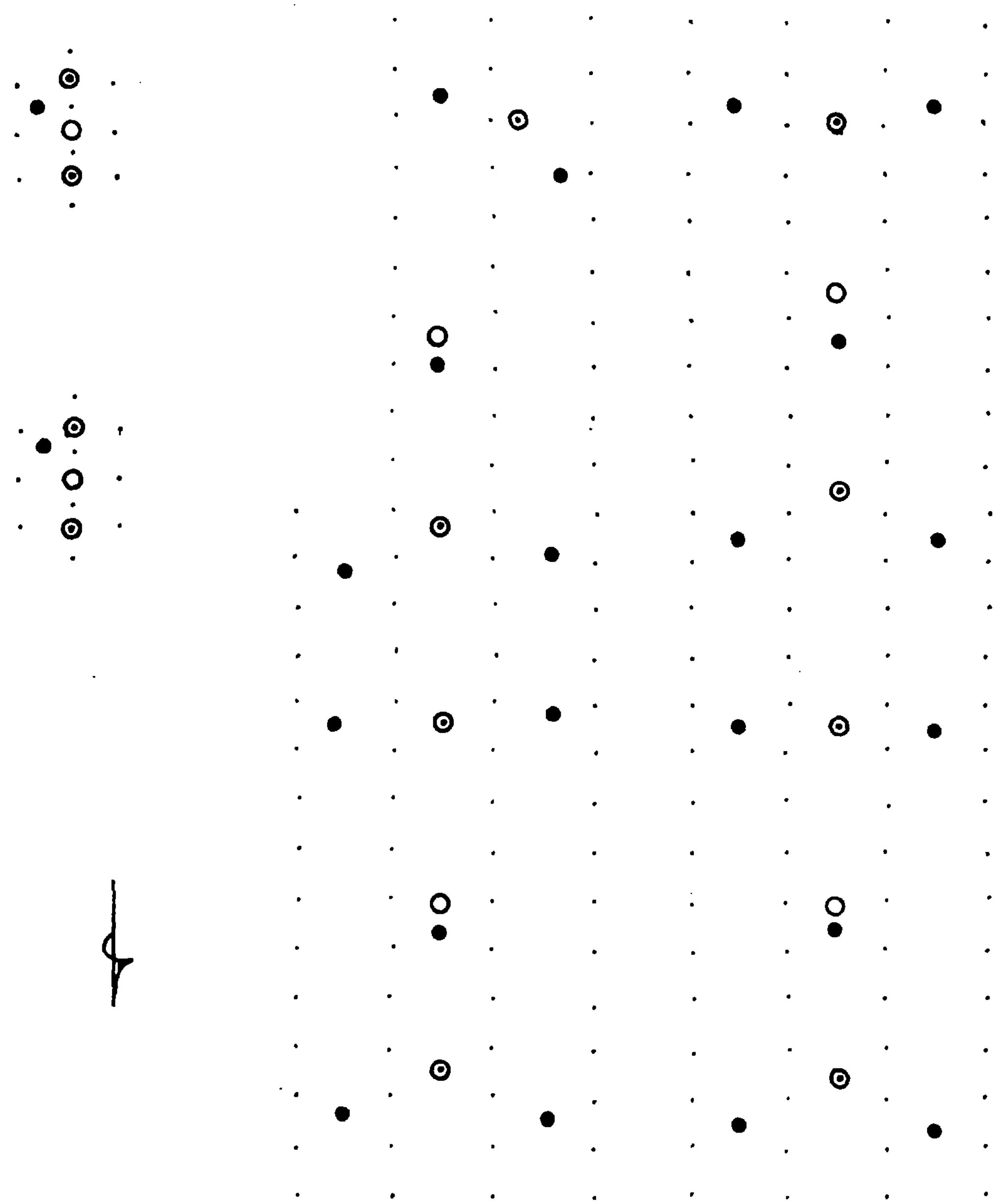
Beginning in mid-March, 1977, soil moisture measurements were made on six samples from the experimental screening area and four from the control (Figures 13 & 14). One measurement was made in each of the gas-barrier techniques. Samples were collected at approximately two-week intervals at times when the moisture content was considered to be the lowest, i.e. before irrigation or before a rain was expected. A sample was obtained using a 3-inch diameter soil auger in the following manner: two 8-inch deep holes



Legend:

- · Trees
- ○ Gas Sample Points
- ● Nutrient Sample Points
- ⊙ Moisture Sample Points

Figure 13. Location of soil variable sampling stations on experimental landfill plot.



Legend:
- • Trees
- o Gas Sample Points
- ● Nutrient Sample Points
- ⊙ Moisture Sample Points

Figure 14. Location of soil variable sampling stations on control plot.

were dug in the same general area and the soil from these two holes was placed into a bucket and mixed with a spade. A 400 ml. metal container was then filled with this soil mixture and capped to retain all the moisture.

After all the samples were collected, each was sieved through a 2 mm. sieve and weighed together with the container and lid and placed in a drying oven @ 100-110°C, then reweighed after twenty-four hours of drying. The soil was then removed from the container and the container and lid were weighed together. This tare weight was then subtracted from both the wet weight of soil plus container weight, and dry weight of soil plus container weight, to give actual wet and dry soil weights. Moisture content percentage was then calculated from these adjusted soil weights to give percent moisture on a dry weight basis.

Soil Nutrient Element Analysis--

On October 15, 1976, June 15, 1977 and October 20, 1977, seven soil samples were collected from the experimental screening area and four from the control screening area for chemical analyses. Each sample consisted of combined soils from five 8-inch-deep holes within each representative area (Figure 13 & 14). For each barrier technique the soil from four 8-inch-deep holes was mixed together and the sample was taken from this mixture.

Soil Bulk Density Analysis--

Soils were measured for bulk density in each barrier technique and in both the experimental and control screening area in the summer of 1977.

Measurements were made in the following manner: a 3-inch diameter - 3-inch long metal core (Figure 15) was placed inside a soil auger. A hammer made to fit over the top of the auger was fitted into place and the auger was driven into the soil until it was 3 inches into the ground. The auger was then pulled from the ground, the core with soil inside removed from the auger and placed into a cardboard container. The samples were dried for approximately twenty-four hours @ 90-100°C until all moisture was removed from the soil particles. The soil was then weighed and the data recorded as g/cc.

On the experimental screening area two measurements were taken at each of six locations (i.e. @ the same locations where moisture content samples were collected) (Figure 13). On the control screening area two measurements were taken at each of four locations totaling twenty measurements for both plots (Figure 14). In each of the seven planting techniques, four measurements were taken, for a total of twenty-eight measurements.

Tree Root Biomass--

A measurement of root biomass was obtained for each plant on both plots between June 13 and June 25, 1977. A 3-inch diameter soil auger was used to bore a 12-inch deep hole, 1.5 feet from the base of each tree in the northerly direction. All the material from this hole was placed into a bucket. The roots were then picked from the soil in the bucket and placed in a small envelope. At the end of each day's root collection, the envelopes were placed in a drying oven for approximately twenty-four hours. The soil clinging to the roots was shaken free and the roots were then weighed.

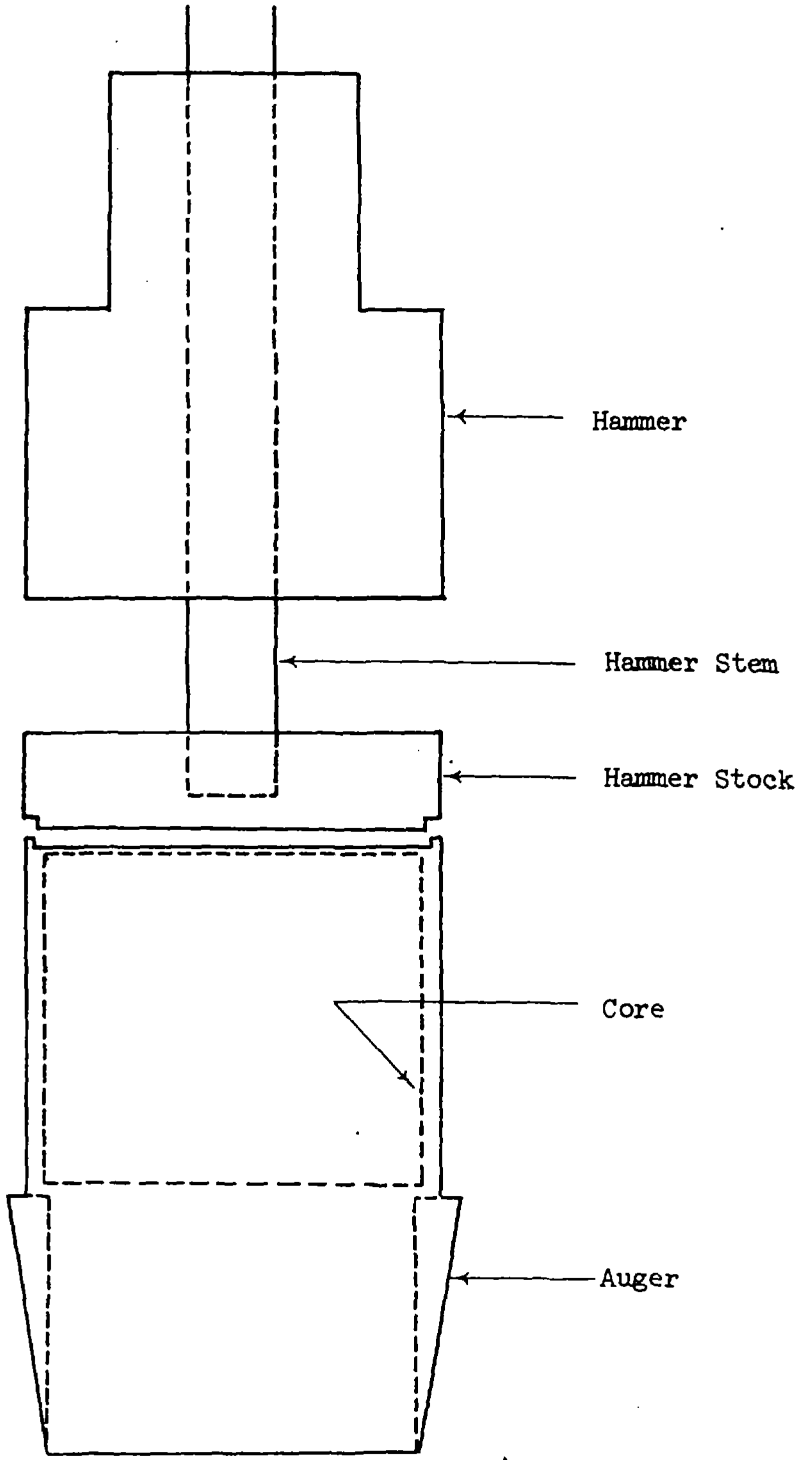


Figure 15. Hammer and auger used for collecting soil bulk density sample.

Tree Shoot Length--

In 1976, shoot length measurements (in cm.) were used as indicators of the vigor and growth response of each tree to its immediate soil environment. Four measurements were taken per tree - the length of the leader shoot which would become the main trunk and the lengths of the three next longest shoots.

The nature of shrub growth is different from that of the trees in that no true leader shoot is produced. Therefore, the four longest shoots were measured on these plants instead of a leader and three longest shoots measured on the trees.

In order to measure the shoot length in 1977 for a particular plant, six shoots were selected from each deciduous tree, shrub and Japanese yew in the following manner: when the plants stopped growing, six shoots were randomly selected on each plant. Each shoot was measured from the past year's bud scale scar to the tip of the current year's terminal bud. This was repeated for all deciduous plants and yew except mixed hybrid poplar.

Because evergreen trees and mixed hybrid poplar produce a true leader shoot, it was measured in addition to five other shoots selected at random from each plant.

Tree Stem Basal Area Increment--

On March 14-16, and on September 17-18, 1977, stem diameter (in cm.) was measured on every plant in both plots with metal tree calipers. The following nine species were measured at a point 30 cm. from ground level: red maple, green ash, American sycamore, hybrid poplar, weeping willow, American basswood, ginkgo, honey locust and pin oak. The remaining ten species were measured somewhat lower on the trunk at distances from the ground indicated in Table 7. A small spot of white paint was placed at the point on the trunk where the measurement was taken. This permitted other measurements to be taken at the end of September from the same point. The stem diameters were converted to cross-sectional stem basal area. The data are reported as percent increase in cross-sectional basal area from March to September.

Tree Leaf Weight--

In order to measure the amount of leaf biomass produced by each plant, four leaf weight samples were collected from each plant in 1977. The procedure for deciduous trees and shrubs and Japanese yew follows:

1. Select four shoots at random from a plant, i.e. one from each compass direction (N,S,E&W).

2. From each of these four shoots, collect all the leaves (needles) from last year's bud scar to this year's terminal bud and place those from each shoot in a separate bag. Dry for approximately twenty-four hours at 150°F and then weigh.

For evergreens, excluding Japanese yew:

1. Collect all the needles along the current year's leader shoot and

place them in a bag.

2. Select three other shoots, two from the top whorl and one from the whorl second from the top. Collect needles from these three shoots and place them in three separate bags.

The needles were oven-dried for approximately twenty-four hours at 150°F and then weighed.

TABLE 7. DISTANCE FROM THE SOIL SURFACE AT WHICH STEM INCREMENT WAS MEASURED

Species Latin Name	Common Name	Distance from Soil (cm)
Acer rubrum	Red Maple	30
Euonymus alatus	Euonymus	5
Fraxinus lanceolata	Green Ash	30
Ginkgo biloba	Ginkgo	30
Gleditsia triacanthos	Honey Locust	30
Liquidambar styraciflua	Sweet Gum	8
Myrica pensylvanica	Bayberry	3
Nyssa sylvatica	Black Gum	8
Poplus	Hybrid Poplar	30
Poplus	Mixed Hybrid Poplar	5
Picea glauca	Norway Spruce	3
Platanus occidentalis	American Sycamore	30
Pinus strobus	White Pine	5
Pinus thunbergi	Japanese Black Pine	5
Quercus palustris	Pin Oak	30
Rhododendron elegans	Rhododendron	3
Salix babylonica	Weeping Willow	30
Tilia americana	American Basswood	30
Taxus cuspidata capitata	Japanese Yew	3

Physical Condition of Trees--

At monthly intervals during the summer of 1977, observations were recorded for every tree which showed signs of stress. Leaf loss, scorch, chlorosis, dieback and wilt were included as signs of stress. At the end of the growing year, each tree was given a number from 0 to 5 based on the physical appearance of the tree. Zero indicated a dead tree and five the healthiest.

Statistical Methods

Analysis of variance, Student's "t" and multiple stepwise regression techniques were employed for data analysis (135). Library programs of the Bio-Med (BMD) series and Statistical Analysis System (SAS) at the Rutgers University Computer Center were employed.

In the analysis of variance, the response variables were leaf weight, shoot length, root biomass and basal stem area increment. Data for these variables were collected on each of the ten replicates for each species on the experimental and control plots, as well as on all ten trees planted in each gas-barrier technique.

In the regression analysis, American basswood was chosen for study because it was growing in those areas (i.e on the gas-barrier techniques) which exhibited a wide range for the soil variables included in the analysis. Ten independent variables were considered: soil gases (six variables) - oxygen, lowest oxygen, carbon dioxide, highest carbon dioxide, methane, highest methane; soil temperature (two variables) - temperature and highest temperature; soil moisture content (one variable) and soil bulk density (one variable). The limits imposed on the regression were: significant F values, R^2 and all coefficients with $P < 0.05$. A prediction equation was then calculated for each response variable (i.e. leaf weight, shoot length, root biomass, basal stem area).

Environmental Conditions

Weed Growth--

Weeds including goldenrod, ragweed, mustard plant and a variety of grasses established themselves over much of the area on both the experimental and control plots. However, the control plot was covered more quickly and more completely than the experimental plot. The grasses comprised a greater portion of the weeds on the control plot.

The two mounds on the experimental plot and the mound and the trench on the control area supported weed growth similar to the gravel/plastic/vents trench which exhibited the best vegetative growth in general.

Hurricane Effects--

On August 10, 1976, Hurricane Belle passed within 50 miles of East Brunswick, New Jersey, site of the landfill experiment depositing 2.4 inches of rain and reaching wind velocities of 46 miles per hour from the northwest. In spite of the chain lock securing each tree to stakes, the wind caused damage to trees on both the experimental and control plots.

Twenty-one trees on the control plot were shifted substantially in the soil by the strong winds. Seven of these were blown over to the extent that their trunks formed a 45° angle with the ground. The trees most affected were the tallest i.e. green ash (#7 & 61) weeping willow (80, 91, 127) and American sycamore (84 & 86). These seven trees were placed in the erect position and restaked. Tree #154, a rhododendron, was split in half at the base of the stem and had to be removed from the site.

On the experimental plot, three green ash trees (10, 15, 16) were blown about so that a much enlarged hole was created around the base of the trunk. The soil was quite loose in the root zone because some large roots had been moved in the soil. These trees had to be restaked and the soil packed down around the roots to ensure that the small roots again had contact with the soil. One of the green ashes (#10) had broken loose from the chain lock securing it to the stakes, allowing the trunk to rub against one of the stakes and causing the bark and part of the cambium to be scraped off for 14 inches along the trunk. Also affected was a Japanese black pine (#181) which was blown over to about a 45° angle with the soil. This tree was placed in an erect position and the soil packed down to ensure good root contact with the soil.

Drainage--

The overall slope of the sites was measured with an Abney hand level. The slope in the north-south direction on the experimental plot was slightly greater (2°) than on the control (1°) which gave the experimental plot better drainage than the control. The east-west slopes were about 1° on both plots.

The difference in drainage between the two plots was very noticeable following Hurricane Belle in August 1977. Ponding of water was observed on the control plot for five days following the hurricane whereas ponding on the experimental plot lasted only one day.

SIMULATED LANDFILL STUDIES

Selection of Gas Concentrations for Greenhouse Studies

In order to select realistic concentrations of landfill gas components for inclusion in simulated mixtures for greenhouse studies, soil gas concentrations of twenty sanitary landfills visited throughout the continental United States were measured between August 1975 and January 1977 (52). Of these landfills five had completed filling since 1966 or were still operating when the data were collected. Only landfills which contained municipal refuse which was not burnt were used in this study. Seven of the sanitary landfills had a reported average refuse depth of more than twenty feet and twelve had an average depth of less than twenty feet of refuse. Information concerning the landfills was obtained by questioning landfill operators and public works employees.

Sampling sites were chosen by visually examining the landfill for types of vegetative growth and sampling was done on areas indicative of the types of vegetation observed. The samples were obtained by making a hole to a depth of one foot with a $\frac{1}{2}$ inch diameter bar-hole maker. Once the hole was made the bar-hole maker was quickly removed and a hollow steel probe was inserted into the hole which was then sealed with a rubber stopper. A MSA Model 2A Explosimeter was then used to extract a sample through the probe. This instrument provides a reading of the percent combustible gas in the sample.

The MSA Explosimeter is sensitive to all combustible gases. The sample is drawn over a heated catalytic filament which forms part of a balanced Wheatstone bridge electrical circuit. The combustion raises the temperature of the filament, thereby increasing resistance in proportion to the concentration of combustibles in the sample. This unbalances the electrical circuit causing a deflection of the current meter pointer which indicates on the scale the concentration of combustible gas in the sample. This instrument was calibrated by means of a MSA (Part #454380) calibration kit supplied by the manufacturer. Frequent calibration is necessary since the filament may become contaminated with use.

The approximate concentrations of oxygen and carbon dioxide were obtained by using Bacharach Fyrite Model CPD O_2 and Model CUD CO_2 analyzers. The Fyrite gas analyzers operate on the Orsat principle of gas analysis. A sample of the gas to be analyzed is contained in a space of known volume from which the O_2 or CO_2 is removed from the gas mixture by selective absorption into fluids in the analyzer. The removal of the O_2 or CO_2 from the sample decreases the pressure exerted by the gas sample on the fluid. The fluid is in contact with the atmospheric pressure by means of an elastic diaphragm so that as the gas is absorbed the fluid replaces the gas mixture being measured. The intrusion of the fluid into the space originally occupied by the sample provides a measurement of the amount of O_2 or CO_2 removed.

The quality of the fluid in the CO_2 analyzer is determined by exhaling a deep breath into the instrument and if it fails to record 2 to 4% CO_2 in the sample the fluid is replaced. The fluid in the O_2 analyzer is checked by sampling the ambient air and if it fails to read 20 or 21% O_2 in the sample the fluid is replaced.

The Effect of Simulated Landfill Gas on Two Maple Species

To investigate the ability of tree seedlings to survive in soil atmospheres contaminated with excessive amounts of carbon dioxide (CO_2) and methane (CH_4), two species of maple were chosen: red maple (_Acer rubrum_) because of its ability and sugar maple (_Acer saccharum_) because of its inability to withstand flooding. These species were compared in order to determine if the species more tolerant to flooding was also more tolerant to soil atmospheric contamination with CO_2 and CH_4.

Cultural Methods--

One-year old red and sugar maple seedlings were purchased bare-rooted from Hess Nursery of Cedarville, New Jersey. The seedlings were planted (5 each) in 12 20-gallon modified galvanized steel trash cans (Figure 16) containing a soil mix of 1 part peat and 2 parts loam, on May 1, 1977. The soil was sterilized by heating to 180°F in an electrical sterilizer for 24 hours.

Fumigation Methods--

The seedlings were divided into three treatments with 20 seedlings (10 of each species) in each treatment (Figure 17). For treatment 1 the soil in each can was fumigated with a gas mixture containing approximately 3% O_2, 40% CO_2, 50% CH_4 and 7% N_2. Treatment 2 was a control with compressed ambient air forced through the soil. The compressed air and the gas mixtures were supplied by Matheson Gas Products Inc. of East Rutherford, New Jersey. In treatment 3 the seedlings were flooded by filling the cans with water to a depth of several inches above the soil line. In order to fumigate the soil, two cans were attached in series to a cylinder containing the gas mixture and equipped with a two-stage gas regulator. Prior to planting the seedlings it was determined that a gas flow of 120 to 250 ml. per minute was necessary for each pair of cans in order to adequately saturate the soil.

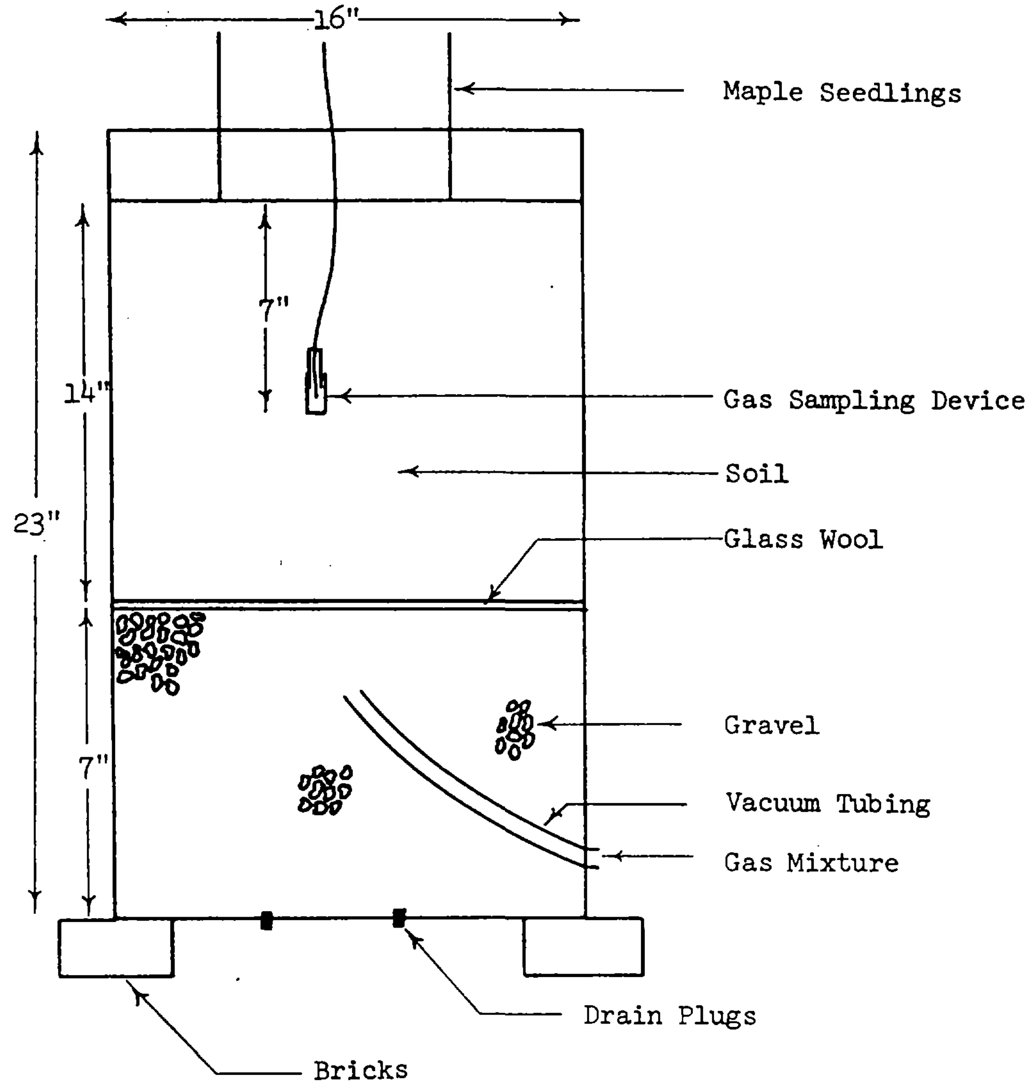


Figure 16. Modified galvanized steel trash can used to fumigate maple seedlings.

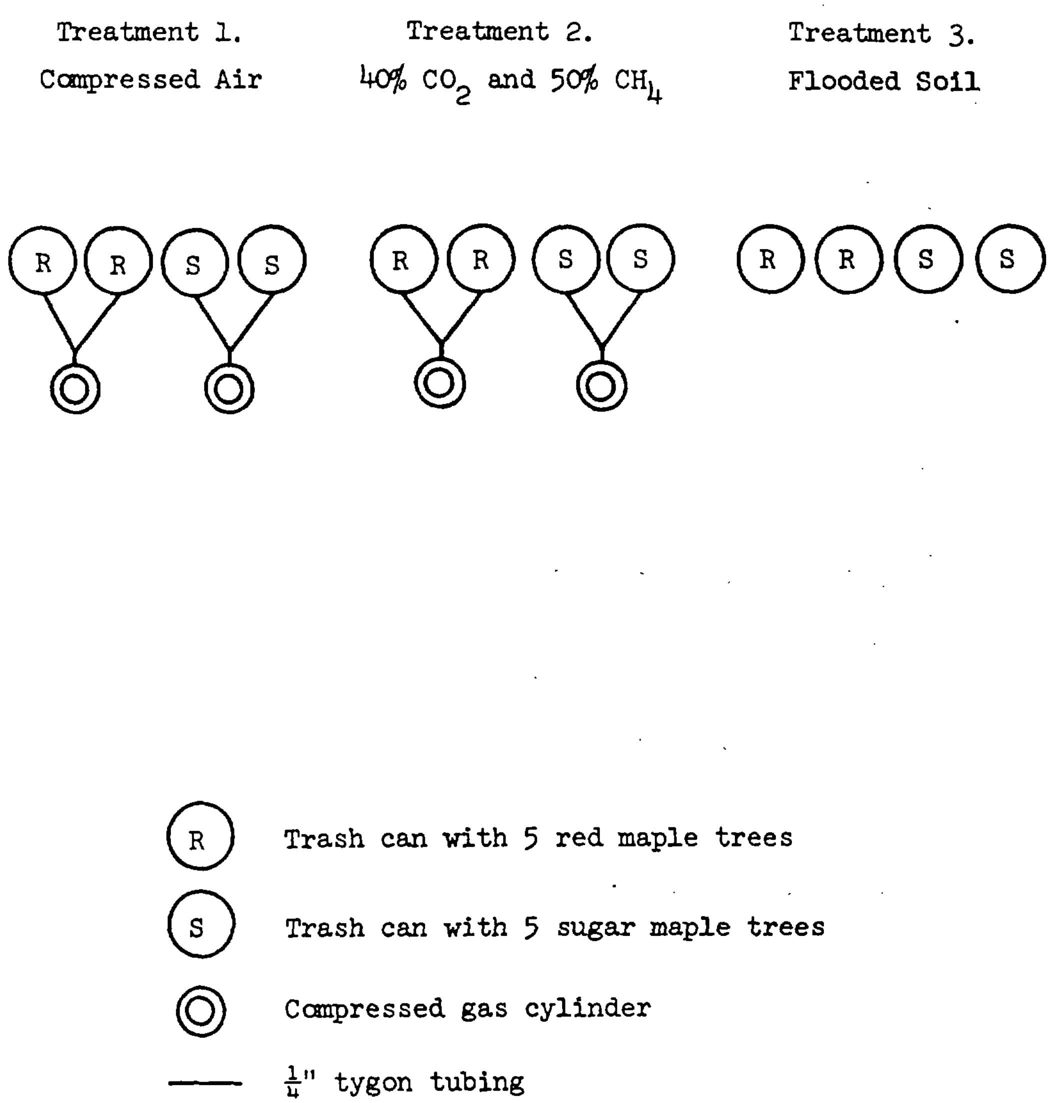


Figure 17. Design of red and sugar maple fumigation experiment.

The gas flow was established by disconnecting the tubing from the cylinder to the two trash cans and establishing the desired flow in air with a soap bubble flowmeter. This done, the tubing was reconnected. The flow of gas through the soil was not determined.

The composition of the soil atmospheres was monitored by extracting a 0.5 ml. sample of air from devices (Figure 5) buried at a 7 inch depth in the soil and analyzing it with a Carle model 8500 gas chromatograph (134).

The fumigations did not begin until August 9, 1977 by which time the seedlings had completed most of their seasonal growth. They were from 2-to 4-feet tall at this time.

Analytical Methods--

Transpiration measurements--The physiological condition of the seedlings was monitored by periodically measuring the rate of transpiration with a Lambda Instruments Diffusive Resistance Porometer. This instrument measures water vapor that evaporates off of the leaf surface and consists of a sensor which is a modified hygrometer whose electrical resistance varies inversely with humidity and a portable resistance meter. The instrument was calibrated by means of an acrylic plate with holes drilled in it which was placed over filter paper saturated with water to simulate the stomatal resistance. If the root system was damaged, the tree would be unable to take up water fast enough to support normal transpiration. Readings were taken only on leaves which were fully illuminated and in the upper one-third of the seedling. Measurements of transpiration rate were obtained only on sunny days. It required two to three hours to take transpiration measurements on all sixty seedlings. Therefore, sampling had to be performed in such a way as to compensate for the changes in illumination caused by movement of the sun or the occurrence of clouds. This was done by taking readings on only two seedlings in each can before moving on to the next one. After all the cans had been sampled in this manner, measurements were begun again on the remaining three seedlings in each can. If the weather changed after the sets of two readings were completed but before the rest of the data were collected then only the data obtained in the first sets were reported. If the weather conditions changed noticeably before the first sets of two readings were completed, the data were not reported.

Soil gas analyses--The composition of the soil atmosphere in treatments 1 and 2 was monitored regularly during the course of the experiment. From August 9 through August 25, the flow of gas as it came out of the cylinder was 120 ml. per minute for each group of two trash cans. From August 26 through August 29 treatments 1 and 2 were discontinued due to an interruption of the gas delivery. From August 30, for the duration of the experiment, the flow of gas coming out of the cylinder was 220 ml. per minute for the two cans containing the sugar maples and 250 ml. per minute for the two cans containing the red maples. The increased flow of gas to the red maples was found to be necessary in order to maintain a soil atmosphere similar to that given the sugar maples. On September, 20, 21 and 22, the gas treatment was discontinued to the red maples receiving CO_2 and CH_4 due to problems with the regulator. The control seedlings were fumigated with compressed air at the same rate of flow used for the corresponding species in treatment 1.

This experiment was terminated on September 27, 1977.

Statistical methods--Where there were two means to be compared the data were statistically analyzed by means of Student's "t" test. Where more than two means were involved statistical significance was determined by means of analysis of variance (135).

The Effect of Simulated Landfill Gas on Tomato Plants in Solution Culture

Cultural Methods--

Rutgers tomato plants were grown in specialized 4-liter culture vessels in sand solution culture (Figure 18). The plants were watered daily with a solution containing nutrients in the following molar concentrations; .0019 M K_2SO_4, .0016 M KH_2PO_4, .0045 M $Ca(NO_3)_2$, .001 M $MgSO_4$, .0004 M $(NH_4)_2SO_4$, .0005 M H_3BO_4, .0005 M $FeSO_4$, .00044 M EDTA and a trace element mix.

When the plants were about 1 foot high, the lower leaves were pruned and lids were placed on the glass vessels (Figures 18 & 19). Cotton impregnated with heavy duty silicon vacuum grease and vaseline was used to provide a seal around the stems of the plants. Tygon tubing was attached to the vessel outlets for drainage and to the gas inlets and outlets for gas flow. Flower and lateral shoot buds were pruned in order to concentrate the growth to the main shoot.

Fumigation Methods--

The plants were fumigated by circulating gas mixtures, supplied by Matheson Gas Products Inc. of East Rutherford, New Jersey, through the vessels. The gas was first circulated at a rate in excess of 1000 ml. per minute for a few minutes and then stopped. The tubing was then removed, and a flow of 120 ml. per minute was established through the tubing into ambient air. This done, the tubing was reconnected to the group of four vessels. This was repeated for each treatment. The rate of gas flow was determined daily after watering by means of a 100 ml. soap bubble flowmeter. The pressure resulting from this rate of flow into air was enough to maintain the composition of the soil atmosphere in the vessels relatively constant with no measurable outward flow. Transpiration by the tomato plants resulted in the loss of about 400 ml. of water a day. The gas was able to fill this void.

Tomato experiment 1 was designed to examine the response of tomato plants to a soil atmosphere having suppressed O_2 concentrations in conjunction with elevated concentrations of CO_2 and CH_4. This experiment consisted of twenty-one plants which were divided into three treatments with seven replicates for each. The composition of the atmospheres used for the various treatments is given in Table 8. The fumigation was started on November 11, 1976 and was discontinued on December 9, 1976.

Experiment 2 was designed to determine the effects of a soil atmosphere containing high concentrations of both methane and carbon dioxide on the growth of tomato plants compared with soil atmospheres containing only carbon dioxide or methane. This experiment consisted of twenty plants which were divided into five treatments with four replicates for each. The composition of the atmospheres used for the various treatments is given in Table

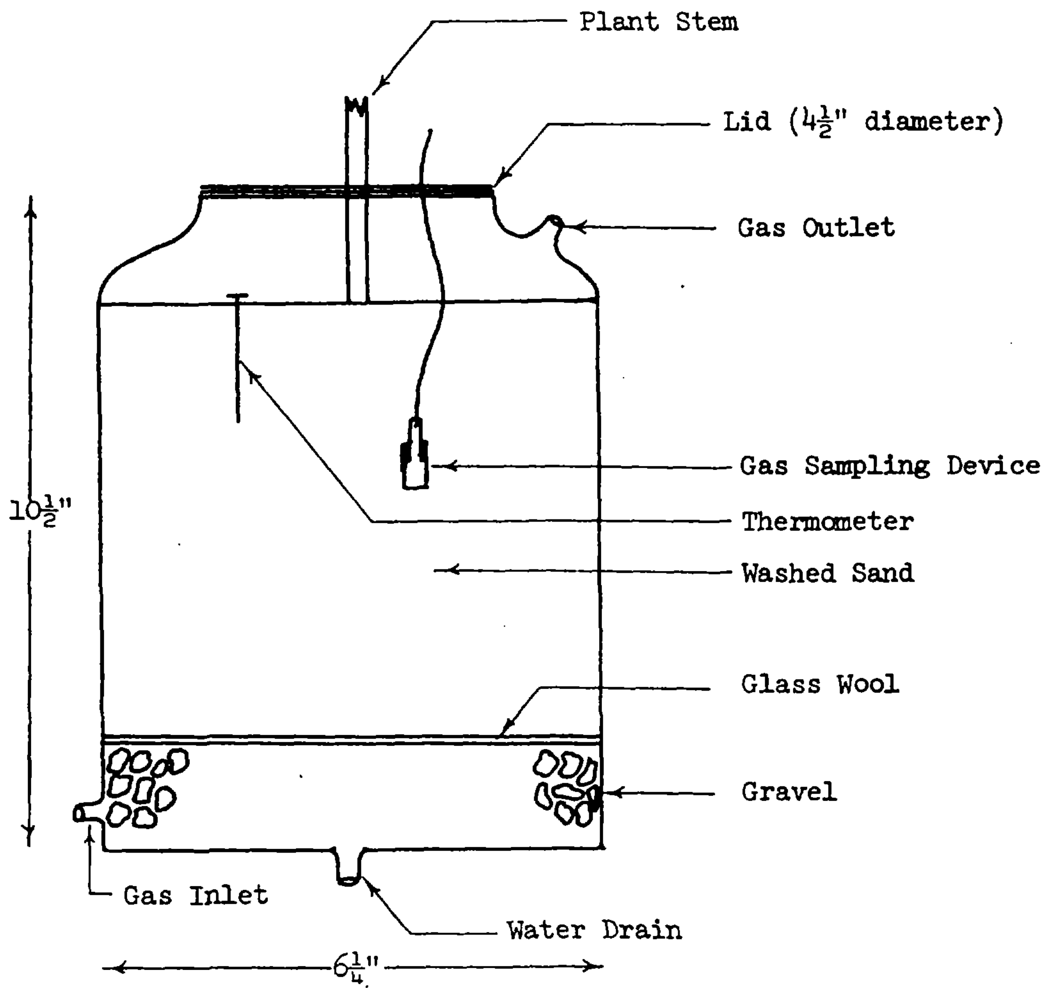
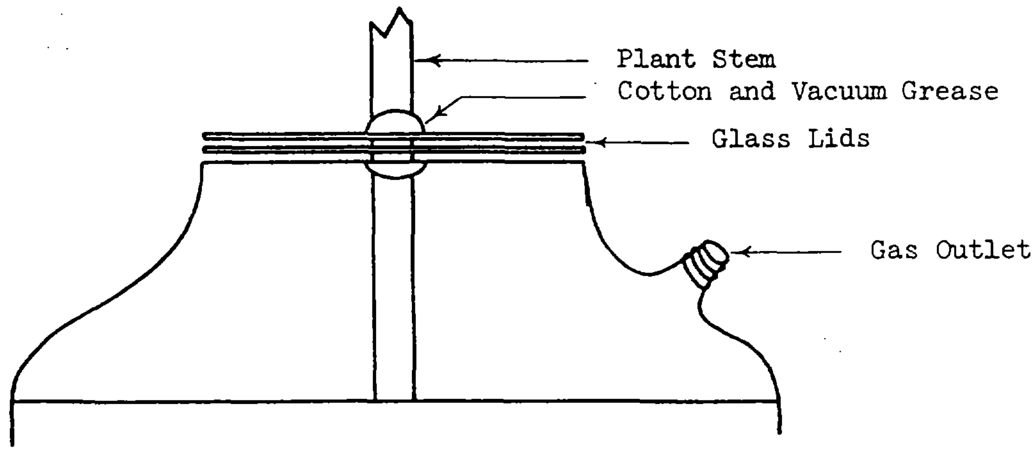
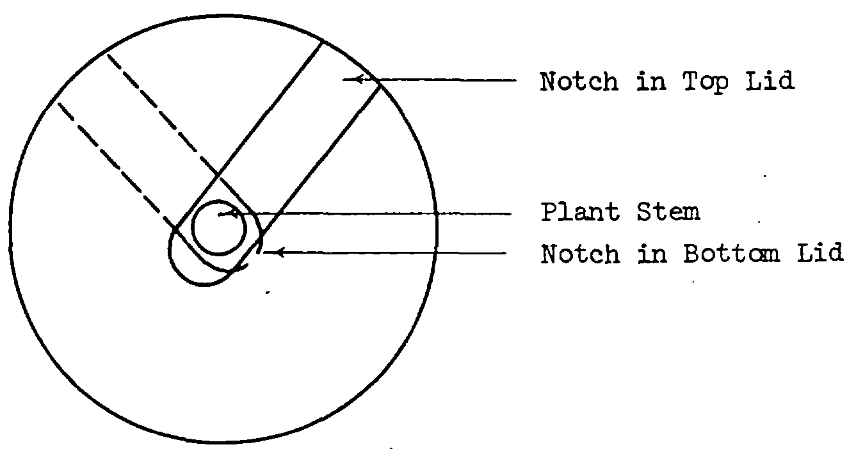


Figure 18. Culture vessel for tomato plant fumigations.



A. Partially Dissected Side View



B. Top View

Figure 19. Lids for culture vessels.

9. This experiment was conducted twice; from March 22, 1977 to March 30, 1977 and again from April 19, 1977 to May 1, 1977. The first trial was of shorter duration (8 days) than the second trial which lasted twelve days.

TABLE 8. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 1

	Treatment		
	A*	B	C
% O_2	21	7	7
% CO_2	trace	trace	10
% N_2	79	93	58
% CH_4	0	0	25

* Atmospheric air

TABLE 9. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 2

	Treatment				
	A*	B	C	D	E
% O_2	21	5	5	5	5
% CO_2	trace	trace	40	40	trace
% N_2	79	95	55	5	45
% CH_4	0	0	0	50	50

* Atmospheric air

Experiment 3, was designed to determine the effects of a soil atmosphere containing high concentrations of carbon dioxide on the growth of tomato plants exposed to differing oxygen concentrations in the soil. This experiment consisted of twelve plants which were divided into three treatments with four replicates for each. Due to the results of previous experiments in which plant response to low O_2 and ambient air fumigations were identical, air controls were eliminated. The composition of the atmospheres used to fumigate the culture vessels in the various treatments is given in Table 10. The fumigation was started on October 15, 1977 and was completed on November 10, 1977.

Experiment 4, was designed to determine the effects of a soil atmosphere containing high concentrations of methane or carbon dioxide on the growth of tomato plants. This experiment consisted of sixteen plants which were divided into four treatments with four replicates for each. The composition of the atmospheres used to fumigate the culture vessels used in the various treatments is given in Table 11. The fumigation began on December 10, 1977 and was discontinued on January 9, 1978.

TABLE 10. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 3

	Treatment		
	A	B	C
$\%O_2$	4	15	4
$\%CO_2$	trace	30	30
$\%N_2$	96	55	66

TABLE 11. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 4

	Treatment			
	A	B	C	D
$\%O_2$	5	15	15	5
$\%CO_2$	trace	20	10	trace
$\%N_2$	95	65	75	50
$\%CH_4$	0	0	0	45

Analytical Methods--

Growth measurements--The height of the tomato plants was determined by measuring the distance from the glass lid to the tip of the uppermost fully expanded leaf. Adventitious root development was reported only when it occurred above the lid.

Soil gas analyses--The soil atmosphere in the culture vessels was monitored with a Carle model 8500 gas chromatograph as described previously.

Nitrogen analyses--The total nitrogen content of the dry plant tissue was determined by using the Kjeldahl method, which gives a reading in mg.of N per 100 mg. of dry plant tissue (114).

SECTION 6

RESULTS

COMPOSITION OF THE SOIL ATMOSPHERES OF TWENTY COMPLETED SANITARY LANDFILLS

The majority of the CO_2 readings in the atmospheres occurred in the 0 to 4.9% category (Table 12). The majority of the O_2 readings in the atmospheres of the twenty landfills occurred in the 15 to 21% concentration category (Table 13). The combustible gas readings were concentrated in the two extreme categories, between 0 and 4.9% and greater than 25%, with the majority of the readings occurring in the 0 to 4.9% category (Table 14). This tendency of the readings to polarize at the extreme ends of the scale was also noted with respect to the CO_2 readings (Table 12). The landfills completed prior to 1966 exhibited lower average CO_2 and combustible gas readings in conjunction with higher average O_2 readings than the landfills completed since 1966 (Table 15). These differences were not statistically significant. The landfills having less than 20 feet of refuse did not exhibit any significant differences in the average concentrations of the soil atmospheric components when compared with the landfills having more than 20 feet of refuse (Table 16).

TABLE 12. PERCENT FREQUENCY OF CO_2 READINGS* OF SOIL ATMOSPHERES ON TWENTY COMPLETED SANITARY LANDFILLS

% Range	% Frequency
0 - 4.9	67.2
5 - 9.9	10.3
10 - 14.9	6.0
15 - 19.9	1.7
20 - 40+	14.7

* 116 samples at one foot depth.

TABLE 13. PERCENT FREQUENCY OF O_2 READINGS* OF SOIL ATMOSPHERES ON TWENTY COMPLETED SANITARY LANDFILLS

% Range	% Frequency
0 - 4.9	7.0
5 - 9.9	7.0
10 - 14.9	14.4
15 - 21	71.6

* 128 samples at a one foot depth.

TABLE 14. PERCENT FREQUENCY OF COMBUSTIBLE GAS READINGS* OF THE ATMOSPHERES ON TWENTY COMPLETED SANITARY LANDFILLS

% Range	% Frequency
0 - 4.9	81.6
5 - 9.9	4.6
10 - 14.9	0.6
15 - 19.9	0.5
20 - 24.9	0.3
25 - 40+	12.3

* 350 samples at a one foot depth.

TABLE 15. MEAN PERCENT CO_2, O_2 AND COMBUSTIBLE GAS AT 1-FOOT DEPTH WITH AGE OF SANITARY LANDFILL

Gas %	Completed Before 1966*	Completed After 1966**
O_2	19.0	15.2
CO_2	2.2	8.7
Combustible Gas	1.7	8.9

* Average of 5 landfills.
** Average of 15 landfills.

TABLE 16. MEAN PERCENT O_2, CO_2 AND COMBUSTIBLE GAS AT 1-FOOT DEPTH WITH DEPTH OF REFUSE IN THE SANITARY LANDFILL

Gas %	>20 Feet*	<20 Feet**
O_2	15.9	17.3
CO_2	7.3	5.3
Combustible Gas	5.0	8.9

* Average of 7 landfills.
** Average of 12 landfills.

COMPOSITION OF THE SOIL ATMOSPHERE AND ITS INFLUENCE ON THE DISTRIBUTUION OF NATIVE VEGETATION ON THE COMPLETED EDGEBORO SANITARY LANDFILL

Data for in situ measurements of gas composition on the Edgeboro Landfill by the macro-sample method are presented in Tables 17, 18, and 19 and for the micro-sample method (gas chromatography) in Table 20 and 21. At all stations monitored there was a consistent relationship between the occurrence of high levels of combustible gas and poor or no growth of vegetation. This relationship was also evident when comparing high levels of CO_2 and low levels of O_2 with poor growth of vegetation.

The four stations A, B, C, and D, monitored for the entire fifteen months (Table 2) exhibited very little fluctuation in composition of the soil atmosphere. This was also true for the stations E, F, G, and H monitored for only five months.

The cover material was significantly thicker ($P < 0.05$) where the vegetation was growing well (Table 22).

TABLE 17. PERCENT COMBUSTIBLE GAS FROM 1-FOOT DEEP TEST HOLES ON COMPLETED EDGEBORO LANDFILL

	Sampling Data					
Station	6/6/76*	7/15/76**	4/15/77*	8/10/77**	9/14/77*	9/20/77*
A	>45	40	39	40	39	40
B	≥45	≥45	≥45	≥45	36	≥45
C	4.5	3	3.3	4.5	0.8	2.2
D	0	Wet	1.0	Wet	0	0
E	--	--	15	≥45	--	≥45
F	--	--	1	0	0	5
G	--	--	45	≥45	--	32
H	--	--	0	0	--	0.5

(continued)

TABLE 17. (continued)

Station	6/6/76*	7/15/76**	4/15/77*	8/10/77**	9/14/77*	9/20/77*
			Sampling Data			
I	--	--	--	--	--	0
J	--	--	--	--	--	$\geq$45
K	--	--	--	--	--	0

* Average of 4 readings. -- no reading taken.
** Average of 2 readings. Data obtained with a MSA explosimeter.

TABLE 18. PERCENT O_2 *FROM 1-FOOT DEEP TEST HOLES ON COMPLETED EDGEBORO LANDFILL

Station	7/15/76**	4/15/77***	8/10/77**
		Sampling Date	
A	5.0	3.5	7.5
B	6.0	7.0	2.5
C	20.0	19.4	18.75
D	wet	20.0	wet
E	---	4.2	14.5
F	---	21.0	20.0
G	---	8.5	7.5
H	---	20.5	20.5

* Readings were obtained with Bacharach, Fyrite O_2 analyzer.
** One reading.
*** Average of 2 readings.

TABLE 19. PERCENT CO_2 *FROM 1-FOOT DEEP TEST HOLE ON COMPLETED EDGEBORO LANDFILL

	Sampling Date		
Station	7/15/76**	4/15/77***	8/10/77**
A	17.0	21.0	16.0
B	18.0	25.0	34.5
C	0.5	1.0	1.5
D	wet	0.0	wet
E	---	12.5	9.0
F	---	0.5	1.5
G	---	16.0	20.0
H	---	0.0	0.0

* Readings were obtained with Bacharach, Fyrite CO_2 analyzer.
** One reading.
*** Average of 2 readings.

TABLE 20. GAS CHROMATOGRAPHIC ANALYSIS OF COMPOSITION OF SOIL ATMOSPHERE AT DEPTH OF 10-INCHES AT 6 STATIONS ON COMPLETED EDGEBORO LANDFILL, JULY 14, 1977

	Gas (% by volume)*			
Station	O_2	CO_2	CH_4	N_2
A	0.5	38.0	49.5	12.0
B	2.7	35.3	39.0	23.0
C	18.2	4.2	3.6	74.0
D	20.3	1.7	0.0	78.0
E	2.0	35.5	34.5	28.0
F	18.2	4.2	0	77.6

* Corrected to 100 percent.

TABLE 21. GAS CHROMATOGRAPHIC ANALYSIS OF COMPOSITION OF SOIL ATMOSPHERE AT DEPTH OF 10-INCHES AT 6 STATIONS ON COMPLETED EDGEBORO LANDFILL, OCTOBER 13, 1977

	Gas (% by volume)*			
Station	O_2	CO_2	CH_4	N_2
A	0.8	37.5	46.7	15.0
B	1.5	32.0	48.5	18.0
C	19.0	1.0	0.0	80.0

(continued)

TABLE 21. (continued)

Station	Gas (% by volume)*			
	O_2	CO_2	CH_4	N_2
D	20.2	1.2	2.6	76.0
E	3.0	30.0	36.0	31.0
F	18.8	2.2	1.0	78.0

* Corrected to 100 percent.

TABLE 22. DEPTH OF SOIL COVER* AT STATIONS ON EDGEBORO LANDFILL AND GROWTH STATUS OF VEGETATION

Good Vegetative Growth		Poor Vegetative Growth	
Station	Depth of Soil Cover (inches)	Station	Depth of Soil Cover (inches)
C	10.0	A	5.1
F	10.1	B	7.4
D	8.2	E	3.9
H	9.5	G	3.0
K	6.7	J	3.9
I	6.5		
Mean	8.5**	Mean	4.7

* Each value is the mean of 5 observations.
** Significantly greater ($P < 0.05$).

SPECIES SCREENING EXPERIMENT

Relative Viability of Plants

Sixty-two trees died on the experimental and control plots during this study: 38 on the experimental and 24 on the control plot (Table 23).

TABLE 23. NUMBER OF TREE DEATHS IN SCREENING EXPERIMENT BETWEEN 1976 AND 1977

Species	Summer 1976 Exp.	Summer 1976 Control	Winter 1976-77 Exp.	Winter 1976-77 Control	Summer 1977 Exp.	Summer 1977 Control
Rhododendron	2	2	2	4	6	4
Hybrid Poplar	0	1	1	0	6	2
Mixed Hybrid Poplar	0	2	0	5	0	0
Euonymus	0	0	5	0	1	0
Black Gum	4	1	0	1	1	0
Sweet Gum	1	0	1	0	2	1
Weeping Willow	4	0	0	0	0	0
Red Maple	0	0	0	0	1	0
Ginkgo	0	1	0	0	0	0
Bayberry	0	0	0	0	0	1
Japanese Yew	0	0	0	0	0	1
Norway Spruce	0	0	0	0	1	0
	11	5	9	10	18	9
	16		19		27	

Relative Growth of Surviving Plants

The interpretation of whether a particular species grew significantly better on the control or on the experimental plot depended upon the tree variable measured (Table 24). On the basis of three or more of these dependent (tree) variables, the majority of species grew significantly better on the control than on the experimental plot.

Shoot length was the only tree variable measured both in 1976 and 1977. With respect to shoot length, twelve species on the control plot appeared to grow better during the 1977 season than in 1976; whereas on the experimental plot, only seven species apparently grew better during the 1977 growing season than they did during 1976. This is indicated by the average shoot length calculated for each species - plot combination for each year (Table 24) and reflects the stress on the trees growing on the experimental plot.

TABLE 24. MEAN VALUES FOR THE FIVE TREE VARIABLE FOR EACH SPECIES ON THE EXPERIMENTAL AND CONTROL PLOTS

Species	Plot	Root Biomass (mg)	Leaf Wt. (g)	Visual Obs.	Basal Area % increase [1]	Shoot Length (cm) 1976	Shoot Length (cm) 1977
Red Maple	Cont.	1270	6.4**	4.4*	69.2	20.6	45.5
	Exp.	579	2.4	2.8	39.0	21.6	15.2
Euonymus	Cont.	1807**	1.2**	3.5**	44.5	18.8**	13.2*
	Exp.	691	0.2	1.1	28.9	15.2	3.8
Green Ash	Cont.	1416	10.5**	4.6**	57.1**	30.4	15.5**
	Exp.	681	4.3	3.1	23.8	34.0	5.8
Ginkgo	Cont.	958**	0.36	1.1	12.6	17.8	0.8
	Exp.	477	0.35	1.3	7.4	23.3*	0.8
Honey Locust	Cont.	1370	23.9 **	4.7**	94.7**	10.4	68.6**
	Exp.	821	2.8	1.7	25	11.7	5.1
Sweet Gum	Cont.	1522**	7.6**	4.9**	198 **	12.7	35.3
	Exp.	432	3.7	2.1	86	12.2	17.0
Bayberry	Cont.	868**	2.0	3.4	66.3	10.4	20.3
	Exp.	294	2.3	4.2	46.7	7.4	17.0
Black Gum	Cont.	1098	2.4	4.2	178	7.9	25.6
	Exp.	524	1.8	2.6	211	8.6	20.8
Norway Spruce	Cont.	689	0.37	3.9	34.3	12.2	4.8
	Exp.	497	0.34	2.8	35.6	10.9	6.1
Hybrid Poplar	Cont.	895*	8.0 **	2.5	696	35.0**	85.8
	Exp.	335	1.0	1.3	16	20.0	12.7
Mixed Poplar	Cont.	270	34.0	4.1	4362	25.4	134.1
	Exp.	592	24.0	4.2	1178	31.0	92.9
American Sycamore	Cont.	1375	11.4	4.9**	53.0**	22.6	42.2
	Exp.	778	7.8	2.9	33.5	20.6	43.7
White Pine	Cont.	1829	2.3	4.3**	52.0	20.8	10.9
	Exp.	961	1.7	3.4	40.0	15.2	7.9
Black Pine	Cont.	1281	15.9*	4.9**	68	18.8	19.8**
	Exp.	907	12.0	3.8	65	19.3	14.5
Pin Oak	Cont.	1047	4.5	4.8*	115 *	13.7	23.1**
	Exp.	628	3.6	3.8	76	12.4	13.5
Weeping Willow	Cont.	1864**	11.6*	4.5**	114 **	69.6	217.2**
	Exp.	429	3.9	1.0	.17	75.2	65.6
American Basswood	Cont.	1865**	1.0	2.7	28.8 **	19.8	18.5**
	Exp.	713	1.2	2.7	19.2	19.0	9.9

1 - % increase from March to September

(continued)

TABLE 24. (continued)

Species	Plot	Root Biomass (mg)	Leaf Wt. (g)	Visual Obs.	Basal Area	Shoot Length (cm) 1976	Shoot Length (cm) 1977
				% increase [1]			
Japanese Yew	Cont.	1087	0.98	4.6	19.3**	11.9	12.2
	Exp.	572	0.50	4.3	45	12.7	19.6
Rhododendron	Cont.	0	0	0	0	8.4*	0.0
	Exp.	0	0	0	0	6.1	0.0

* Significant difference between control and experimental plot @ 95% C.L.
** Significant difference between control and experimental plot @ 99% C.L.

The results of Student's "t" tests for the dependent variables (i.e. root biomass, shoot length, leaf weight and basal area) comparing experimental with control plot indicated that black gum exhibited the least difference in growth between the experimental and control plot (Table 25). Rhododendron had the poorest growth of all species in that all replicates on both plots succumbed by the end of the winter of 1976-1977, presumably from the abnormally cold temperatures.

TABLE 25. RELATIVE TOLERANCE OF SPECIES TO LANDFILL CONDITIONS

Rank a	Species	Σ "t" Statistics b
1	Black Gum	2.66
2	Norway Spruce	3.22
3	Ginkgo	4.95
4	Black Pine	6.59
5	Bayberry	6.62
6	Mixed Poplar	8.13
7	White Pine	8.94
8	Pin Oak	8.96
9	Japanese Yew	8.98
10	American Basswood	9.48
11	Américan Sycamore	10.66
12	Red Maple	10.95
13	Sweet Gum	12.62
14	Euonymus	14.25
15	Green Ash	14.87
16	Honey Locust	15.05
17	Hybrid Poplar	20.33
18	Weeping Willow	21.20
19	Rhododendron	All plants died

(continued)

TABLE 25. (continued)

a. Rank 1 = the best growth when experimental plot is compared to the control plot, i.e. most tolerant of landfill conditions.

b. Σ"t" = the sum of the "t" statistics for shoot length in 1976; leaf weight, basal area increase, root biomass and shoot length in 1977 comparing the experimental area with the control.

Soil Variables

Measurements of numerous soil variables throughout the study were made in order to characterize the nature of the stress to which the plants were subjected on the experimental plot and to compare the values for these variables with those in the control plot (Table 26). The mean carbon dioxide, methane and temperature were significantly greater (99% C.L.) and the oxygen and moisture content significantly lower on the experimental plot than on the control plot.

The calcium content (Table 26) was not significantly different between plots immediately after fertilization in June 1977; however, by November, the experimental plot contained less calcium than the control (99% C.L.). The pH was significantly lower on the control before and after fertilization (99% C.L.). There were no other significant differences for any of the other measured nutrients between plots.

The soil textures (Table 26) were different (99% C.L.) between the two plots with the experimental plot consisting of 82.8% sand while the control plot contained 74.0% sand.

The moisture content of the experimental plot and control plots over time during the summer 1977 is represented in Figure 20. For every date the control plot shows a greater moisture content than the experimental plot.

TABLE 26. MEAN VALUES FOR SOIL VARIABLES ON EXPERIMENTAL AND CONTROL PLOTS IN 1977

Soil Variables	Experimental	Control
% O_2	17.8	19.7*
% CO_2	5.5*	1.2
% CH_4	0.9*	0.0
Temperature °F	66.2*	64.3
% Moisture Content	8.1	11.0*
pH	5.0	4.8
Mg	141	143
P	106	97

(continued)

TABLE 26. (continued)

Soil Variables	Experimental	Control
K	252	283
CA	266	229
COND	29	32
NO_3	42	74
NH_4	201	271
Organic Matter	9.6	10
Fe	54.7	82
Cu	196	210
Zn	579	465
Mn	301	385
B	67	62
Sand	82.8	74.0
Silt		
Clay		

* Differences between experimental and control plots significant at 99% C.L.

The average nitrate (NO_3^-) and ammonium (NH_4^+) nitrogen for the experimental and control plots are given in Table 27 for samples collected on three separate dates in 1976 and 1977. There was no significant difference between plots for NH_4^+ nitrogen on any of the three dates in spite of the fact that, in June 1977, the NH_4^+ on the control was much greater in concentration than on the experimental plot. A single very high reading on the experimental plot was the cause for this large difference.

TABLE 27. MEAN VALUES FOR NITRATE AND AMMONIUM NITROGEN ON EXPERIMENTAL AND CONTROL PLOTS

Date	Experimental a			Control b		
	NO_3 lbs/A	NH_4 lbs/A	Ratio NO_3:NH_4	NO_3 lbs/A	NH_4 lbs/A	Ratio NO_3:NH_4
October '76	6.0	58.3	0.10	10.5	48.5	0.22
June '77	67.1	370.0	0.18	103.2	587.1	0.18
November '77	16.8	10.8	1.56	39.5	11.5	3.43*

a. Each number is the average of 7 separate measurements.
b. Each number is the average of 4 separate measurements.
* Significantly greater than experimental plot (95% C.L.).

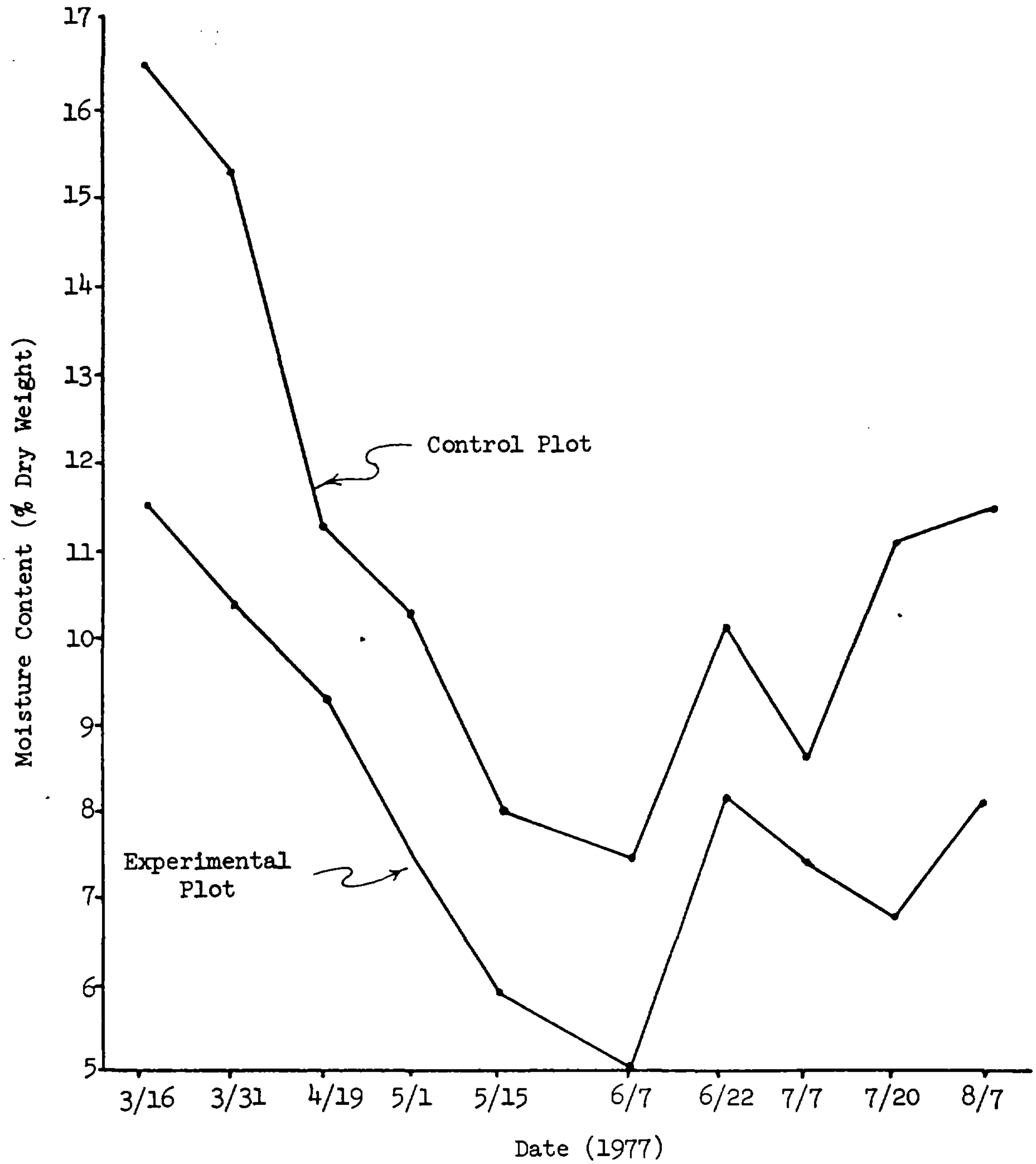


Figure 20. Soil moisture content of experimental and control plots.

The NO_3^- nitrogen content in the experimental plot was statistically similar to that in the control after fertilization in June 1977; however, by November, NO_3^- was significantly lower in the experimental plot (95% C.L.). This resulted in a significantly lower $NO_3^-:NH_4^+$ ratio in the experimental plot than in the control.

Despite the anticipated variability in the independent soil variables from one sampling location to another, and from one sampling date to the next on the control plot, the variability on the experimental plot was far greater than on the control particularly for oxygen, carbon dioxide and methane. This is reflected in the coefficients of variation calculated for each independent soil variable in both plots (Table 28).

TABLE 28. COEFFICIENTS OF VARIATION FOR SOIL VARIABLES ON EXPERIMENTAL AND CONTROL PLOTS

Soil Variables	Experimental	Control
O_2	26.42**	4.02
CO_2	117.34**	36.29
CH_4	388.86**	0.00
Temperature	13.47	12.49
Moisture Content	28.19	29.07
pH	5.63	4.11
Mg	66.86	60.91
P	50.09	77.90
K	44.50	36.97
CA	115.69	119.73
COND	54.00	63.32
NO_3	73.69	59.32
NH_4	104.71	133.57
Organic Matter	77.85	72.17
Fe	149.87	125.19
Cu	106.65	105.84
Zn	51.19	60.22
Mn	82.83	71.53
B	48.25	65.15

** Significant at 99% confidence level.

Root System Profiles

The extent of vertical root penetration for plants growing on the experimental landfill plot was found to be approximately 6-8 inches with the root biomass in the top 6 inches of soil. The data indicated that the roots of plants growing on the control plot penetrated 2-4 inches (or 1.5 times) deeper than on the experimental plot (Table 29).

TABLE 29. DEPTH OF ROOT PENETRATION ON EXPERIMENTAL AND CONTROL PLOTS [a]

Species	Experimental Plot	Control Plot
Basswood	6"	9" *
Sycamore	5"	7"
Sweet Gum	6"	10" *
Black Gum	4"	7"
Black Pine	5"	8" *

a. Average of 4 trees.
* Significant difference between plots @ 95% C.L.

GAS-BARRIER TECHNIQUES

Relative Viability of Plants

All plants in the gas-barrier techniques broke bud soon after planting in the spring of 1976. During the following growing season all ten plants (6 American basswood and 4 Japanese yew) on the clay/vents trench died as well as ten Japanese yew scattered on the remaining barrier techniques (Table 30). All remaining plants survived the winter 1976-1977, however, by the end of the 1977 growing season, six plants had died (4 of these were in trench-clay/vents where 6 plants had died the previous year).

Relative Growth of Surviving Plants

Tree data collected in 1976 and 1977 from the five experimental gas-barrier techniques and the experimental screening area (which serves as a control for the barrier techniques) for American basswood and Japanese yew are given in Table 31. For American basswood, the gravel/plastic/vents trench and clay barrier mound on landfill supported significantly better (99% C.L.) growth than did the experimental screening area which had no special treatment and represented typical landfill conditions. This was true for all the dependent (tree) variables measured excluding root biomass. The variability in root biomass among the basswood trees within each of the planting techniques is reflected in the relatively large variance components among trees compared to those among techniques (Table 32). Because the variability among trees was greater than the variability among barrier techniques, no statistical differences were detected between barrier techniques and experimental screening area despite the large difference in mean root biomass. However, the measurements for root biomass for the gravel/plastic/vents trench, the clay barrier trench and the clay barrier mound fall at the high end of the range of values for all techniques (Table 32).

Japanese yew showed no significant differences between the barrier techniques and the experimental screening area. The variance components for Japanese yew within the barrier techniques were relatively large compared to among techniques for shoot length, leaf weight and root biomass illustrating the great variability among trees compared to the variability among barrier

TABLE 30. OBSERVATION OF DEAD TREES ON EXPERIMENTAL AND CONTROL GAS-BARRIER TECHNIQUES

Seasons					
1976 Growing Season		1976-1977 Winter		1977 Growing Season	
Experimental a	Control a	Experimental	Control	Experimental	Control
American Basswood 216 217 218 219 220 221 Japanese Yew 223 234 225 238 226 239 227 240 231 241 233	American Basswood 192 Japanese Yew 210	No trees died	No trees died	American Basswood 216 217 219 220 Japanese Yew 228 229	No trees died

a. All these plants were replaced in October 1976.

techniques (Table 32), resulting in no significant difference between any of the techniques and the experimental screening area (Table 31).

Soil Variables

The average nitrate (NO_3^-) and ammonium (NH_4^+) nitrogen content in each barrier technique is given in Table 33 for samples collected on two separate dates in 1977. The $NO_3^-:NH_4^+$ ratios in June for all techniques were relatively similar, however, by November, the $NO_3^-:NH_4^+$ ratio was more than two times lower in the clay/vents trench than any other technique. There were no other discernable nutrient trends other than a small decrease in the manganese concentration in the clay/vents trench compared to a relatively large decrease in all other barrier techniques, resulting in a high manganese (45 ppm) concentration by November (Table 33) in the clay/vents trench.

The values for soil oxygen, carbon dioxide, methane, moisture content and bulk density are given in Table 34 for each gas-barrier technique. These data show that the gravel/plastic/vents trench and the two mounds on the experimental plot contained no excessive amounts of carbon dioxide and no methane and that the oxygen concentration was 19.8% or greater. However, carbon dioxide and methane from refuse decomposition contaminated the clay/vents trench and the clay trench. The oxygen concentration in these two latter trenches was also significantly lower than in the control and in the

TABLE 31. MEAN VALUES FOR DEPENDANT TREE VARIABLES FOR EACH GAS-BARRIER TECHNIQUE ON EXPERIMENTAL AREA

Planting Technique	Species	Root Biomass (mg)	Basal Area (% increase)	Visual Obs.	Leaf Weight (g)	Shoot Length (inches) 1976	1977
Trench-Plastic/ Vents/Gravel	Jap. Yew	516	17.0	5.0	1.24	5.2	2.61
	Basswood	800	73.3*	4.5*	3.97*	12.41*	8.98*
Trench-Clay/ Vents	Jap. Yew	74	9.3	2.0	0.41	0.52	2.43
	Basswood	153	0.0	0.0	0.02	1.06	.66
Trench-Clay/ No Vents	Jap. Yew	616	26.0	4.0	0.59	5.1	2.96
	Basswood	1069	23.9	3.5	2.21	7.19	5.58
Mounds-No Clay	Jap. Yew	1051	14.0	3.5	0.64	6.9	1.84
	Basswood	622	31.3	4.5*	1.89	10.98*	6.66
Mound-Clay	Jap. Yew	1062	6.2	2.5	0.85	7.1	2.78
	Basswood	930	60.0*	4.5*	3.40*	12.15*	8.52*
Experimental Screening Area	Jap. Yew	572	45.0	4.3	10.98	5.0	2.17
	Basswood	644	26.8	2.5	1.04	7.46	3.84

* Grew significantly better than the experimental screening area @ 99% C.L.

TABLE 32. VARIANCE COMPONENTS FOR AMERICAN BASSWOOD AND JAPANESE YEW FOR THREE TREE VARIABLES

Shoot Length			
American Basswood		Japanese Yew	
Source of Variation	Variance Components	Source of Variation	Variance Components
Among techniques	73.20	Among techniques	10.59
Among trees	6.53	Among trees	21.50
Among measurements	5.79	Among measurements	2.32
Leaf Weight			
American Basswood		Japanese Yew	
Source of Variation	Variance Components	Source of Variation	Variance Components
Among techniques	15.08	Among techniques	0.08
Among trees	0.68	Among trees	0.36
Among measurements	0.79	Among measurements	0.08
Root Biomass			
American Basswood		Japanese Yew	
Source of Variation	Variance Components	Source of Variation	Variance Components
Among techniques	573,181	Among techniques	57,832
Among trees	916,160	Among trees	286,432

TABLE 33. NITRATE NITROGEN, AMMONIUM NITROGEN AND MANGANESE CONTENTS OF SOIL IN THE BARRIER TECHNIQUES

	Experimental Plot										Control Plot			
	Trench-gravel, plastic, vents		Trench-clay vents		Trench-clay no vents		Mound-no clay		Mound clay		Trench		Mound	
	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77
NO_3 lbs/A	120.0	20.0	61.0	12.0	50.0	12.0	57.0	14.0	46.0	40.0	62.0	36.0	134.0	84.0
NH_4 lbs/A	620.0	8.0	395.0	12.0	280.0	4.0	580.0	2.0	340.0	16.0	360.0	6.0	560.0	22.0
$NO_3:NH_4$ ratio	0.19	2.5	0.15	1.0	0.18	3.0	0.10	7.0	0.14	2.22	0.17	6.0	0.24	3.80
Mn ppm	90.0	6.5	55.0	45.0	50.0	6.0	50.0	8.5	72.5	11.0	44.5	12.5	77.5	14.0

other three techniques on the experimental plot (99% C.L.).

TABLE 34. MEAN SOIL VARIABLE LEVELS IN THE GAS-BARRIER TECHNIQUES

	Gas-Barrier Techniques	Oxygen %Volume	Carbon Dioxide %Volume	Methane %Volume	Moisture Content % Dry Weight	Bulk Density
Experimental Plot	Gravel/Plastic Vents Trench	19.8c*	1.3a	0.0a	9.0b	1.29a
	Clay/Vents Trench	4.3a	22.8c	11.8c	11.0c	1.42a
	Clay Trench	16.3b	7.0b	0.7b	8.4b	1.67b
	Mound	20.3c	0.8a	0.0a	7.3a	1.34a
	Clay Mound	20.3c	0.8a	0.0a	7.5a	1.45a
Control Plot	Trench	19.6c	1.2a	0.0a	10.5c	1.73b
	Mound	19.4c	1.2a	0.0a	10.7c	1.45b

* Means in a column followed by different letters are statistically different at P <0.01.

The moisture content of the soil in the experimental techniques was generally lower than on the control; however, the highest moisture content is in the clay/vents trench. In addition, analysis of variance showed that the soil in the two mounds on the experimental plot had a significantly lower moisture content than any of the other barrier techniques. Analysis of variance of bulk density showed that the values in the clay trench on the experimental plot as well as the trench on the control plot were significantly higher than in any other techniques (99% C.L.).

Statistical Analysis of the Effect of Soil Variables on Tree Variables

Multiple regression analysis of American basswood shoot length data shows a correlation with the linear responses of carbon dioxide, lowest oxygen, highest temperature, bulk density and moisture content, $R^2=53\%$. The general multiple linear regression model given in equation 1 becomes the estimated multiple

$$Y = B_0 + B_1 X_1 + B_2 X_2 + \ldots + B_u X_u + C_i \qquad (1)$$

regression equation for basswood shoot length in equation 2.

$$Y = 45.24 - 0.32 \text{ lowest oxygen} - 0.57 \text{ carbon dioxide} - 0.24 \text{ highest temperature} - 12.34 \text{ bulk density} + 0.78 \text{ moisture content.} \qquad (2)$$

Addition of the quadratic, reciprocal and interactive effects of these variables did not change the coefficient of determination (R^2).

Multiple regression analysis of basswood leaf weight shows a correlation with the linear responses of temperature and bulk density, $R^2 = 41\%$ according to equation 3.

$$Y = 37.86 - 0.37 \text{ temperature} - 6.58 \text{ bulk density} \qquad (3)$$

When the quadratic, reciprocal and interactive effects of these variables were added into the analysis, an increase in R^2 of 22% was obtained with the equation

$$Y = 37.69 - 0.23 \text{ highest temperature} - 10.12 \text{ bulk density} - 0.10 \text{ (moisture content x carbon dioxide)} - 1.42/CO_2 + 4 \qquad (4)$$

giving an $R^2 = 63\%$.

When the tree response root biomass was regressed onto the ten soil variables, it was found to correlate linearly with temperature, bulk density and moisture content, $R^2 = 39\%$ according to the equation

$$Y = 15395.87 - 222.17 \text{ temperature} - 1129.52 \text{ bulk density} + 269.65 \text{ moisture content.} \qquad (5)$$

The addition of quadratic, reciprocal and interactive effect of these variables did not change the coefficient of determination.

Multiple regression analysis of basswood basal area increment data shows carbon dioxide and bulk density to be linearly correlated with the response basal area $R^2 = 48\%$ as seen in equation 6.

$$Y = 141.48 - 2.42 \text{ carbon dioxide} - 59.07 \text{ bulk density.} \qquad (6)$$

Examination of the quadratic, reciprocal and interactive effects produced an increase of 5% in the coefficient of determination to $R^2 = 53\%$ (see equation 7).

$$Y = 169.05 - 69.60 \text{ bulk density} - 2.07 \text{ (bulk density x carbon dioxide)} - 9.60/CO_2 + 4 \qquad (7)$$

THE EFFECT OF CARBON DIOXIDE AND METHANE IN THE ROOT ZONE OF TWO MAPLE SPECIES

At the termination of the 48-day experiment to compare the effects of simulated landfill gases with those of flooding on two maple species, both red and sugar maple trees fumigated with CO_2 and CH_4 were in noticeably worse condition than the controls. The main symptoms were chlorosis and abscission of the lower leaves (Table 35). The flooded sugar maples began to lose their leaves by the 11th day of treatment and defoliation was complete by the 20th day. The red maples still had most of their leaves at the termination of the experiment on the 48th day, however, the leaves which still remained attached were chlorotic. All the red maples that were flooded exhibited adventitious root development below or just above the surface of the water and swelling of the lenticels which were exuding a soft textured white substance.

TABLE 35. NUMBER OF MAPLE SEEDLINGS* EXHIBITING VARIOUS GROWTH CONDITIONS AT TERMINATION OF EXPERIMENT

Condition	1 $CO_2 + CH_4$ Red	Sugar	2 Air Red	Sugar	3 Flooding Red	Sugar
Healthy	1	1	6	8	0	0
Chlorotic						
Lower third of tree	5	1	4	2	3	0
Lower half of tree	2	4	0	0	5	0
> half of tree	2	4	0	0	2	0
Defoliated	0	0	0	0	0	10
Adventitious	0	0	0	0	10	0

* 10 seedlings in each treatment.

The rate of transpiration which is inversely related to stomatal diffusive resistance for the sugar maples fumigated with CO_2 and CH_4 (Treatment 1) was found to be significantly less than the control on day-24 (Tables 36 & 37). The red maple seedlings fumigated with CO_2 and CH_4 showed no significant difference in transpiration from the control at any time during the experiment (Table 36 & 37). The sugar maples grown in flooded soil showed a significant decrease in transpiration rate on the 3rd day of the treatment, whereas the red maples which were flooded did not show a decrease in transpiration until day-42 of the experiment (Tables 36 & 37).

The composition of the soil atmosphere in the garbage cans fluctuated during the experiment. These data are given in Figures 21, 22, 23 and 24.

TABLE 36. MEAN STOMATAL RESISTANCE (SEC/CM)* OF RED AND SUGAR MAPLE SEEDLINGS IN VARIOUS TREATMENTS

	Treatment					
	1		2		3	
Date	$CO_2 + CH_4$		Air		Flooding	
1977	Red	Sugar	Red	Sugar	Red	Sugar
8/9	6.5	N R	N R	7.5	6.5	8.5
8/10	13.5	16.0	11.0	18.5	N R	N R
8/12	9.5	9.0	9.5	11.0	14.0	66.5
8/15	8.0	7.5	7.5	7.0	7.5	26.0
8/18	7.5	14.5	11.0	15.5	16.5	81.0
8/21	7.5	8.0	8.0	8.5	6.0	109.0
8/23	8.5	12.0	9.5	13.0	11.0	120.0
8/29	9.0	15.5	9.5	9.0	13.0	N L
9/2	7.5	21.0	6.5	7.5	7.5	N L
9/8	13.5	89.5	13.5	17.0	17.5	N L
9/21	13.5	60.5	12.0	11.0	24.0	N L
9/27	19.5	49.0	17.5	19.5	28.5	N L

N R No reading.
N L No leaves.
* Each value is the mean of 4 or 10 readings per 10 trees.

TABLE 37. STOMATAL RESISTANCE* OF MAPLE SEEDLINGS FOR TREATMENTS 1 AND 3 RECORDED AS PERCENT OF CONTROL

	Treatment			
	1		3	
Date	$CO_2 + CH_4$		Flooded	
1977	Red	Sugar	Red	Sugar
8/10	122.7	86.4	N R	N R
8/12	100.0	81.8	147.1	604.5**
8/15	106.6	106.1	100.0	328.5**
8/18	63.6	93.4	150.0	522.5**
8/21	93.8	94.1	75.0	1282.3**
8/23	89.5	92.3	115.7	882.3**
8/29	94.7	172.2	136.7	N L
9/2	115.3	280.0**	115.3	N L
9/8	100.0	526.4**	129.6	N L
9/21	112.5	550.2**	200.0	N L
9/27	111.3	251.2**	162.8	N L

(continued)

TABLE 37. (continued)

N R No readings.
N L No leaves.
* Each value is the mean of 4 or 10 readings.
** Statistically significant increase ($P < 0.01$).

EFFECT OF CO_2 AND CH_4 ON THE GROWTH OF TOMATO PLANTS IN SAND SOLUTION CULTURE

Experiment 1

The average composition of the soil atmosphere in the culture vessels for each treatment is given in Table 38. No statistically significant difference was found between the three treatments in terms of total change in height, total dry weight of the leaves or total nitrogen content of the leaf tissue (Table 39). Four of these plants exhibited a reddening of the veins on the intermediate-aged leaves which had been fully expanded at the start of the fumigation. This symptom was not observed on any of the plants treated with low O_2 or air (Treatments A & B). All the plants receiving high CO_2 and CH_4 concentrations exhibited adventitious root development on the stems above the glass lids.

Temperatures in the vessels ranged from a low of 65°F to a high of 81°F during the experimental period.

TABLE 38. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 1

	Treatment		
Gas %	A	B	C
O_2	20.7	12.2	10.5
CO_2	1.1	1.3	7.2
N_2	78.2	86.5	62.3
CH_4	0.0	0.0	20.0

* Mean of 35 to 40 observations, corrected to 100 percent.

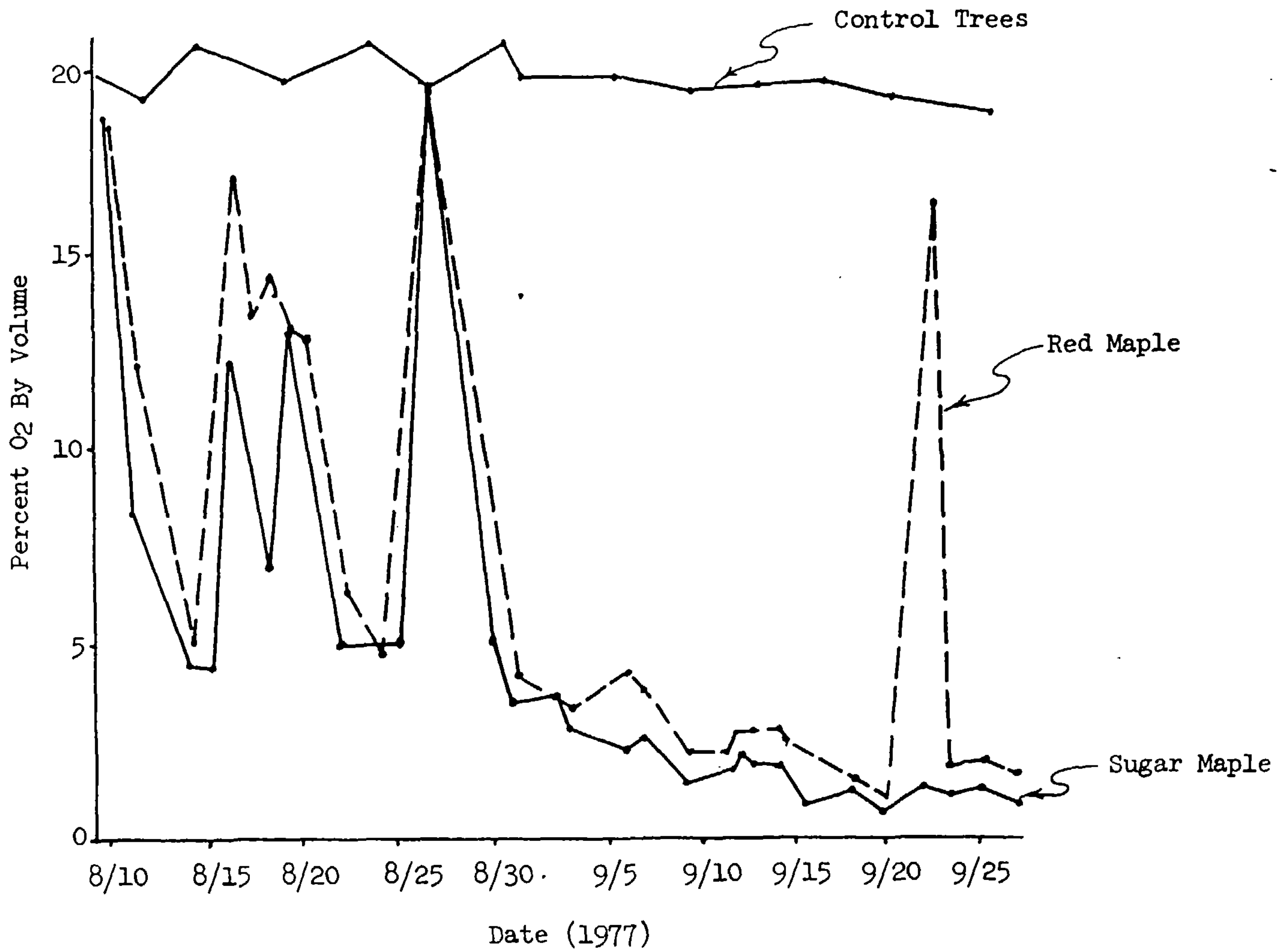


Figure 21. Mean percent O_2 at 7" depth in fumigated trash cans.

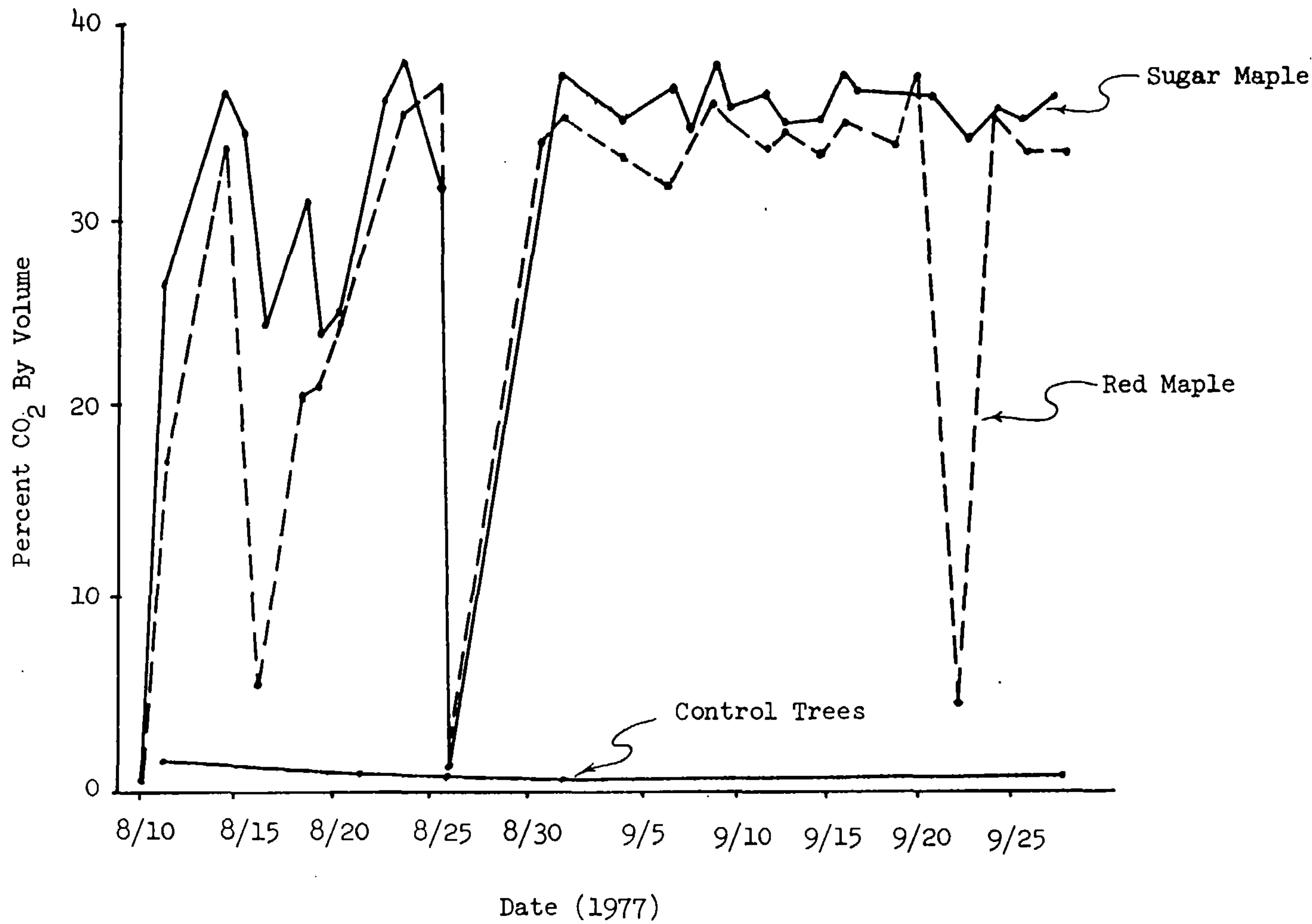


Figure 22. Mean percent CO_2 at 7" depth in fumigated trash cans.

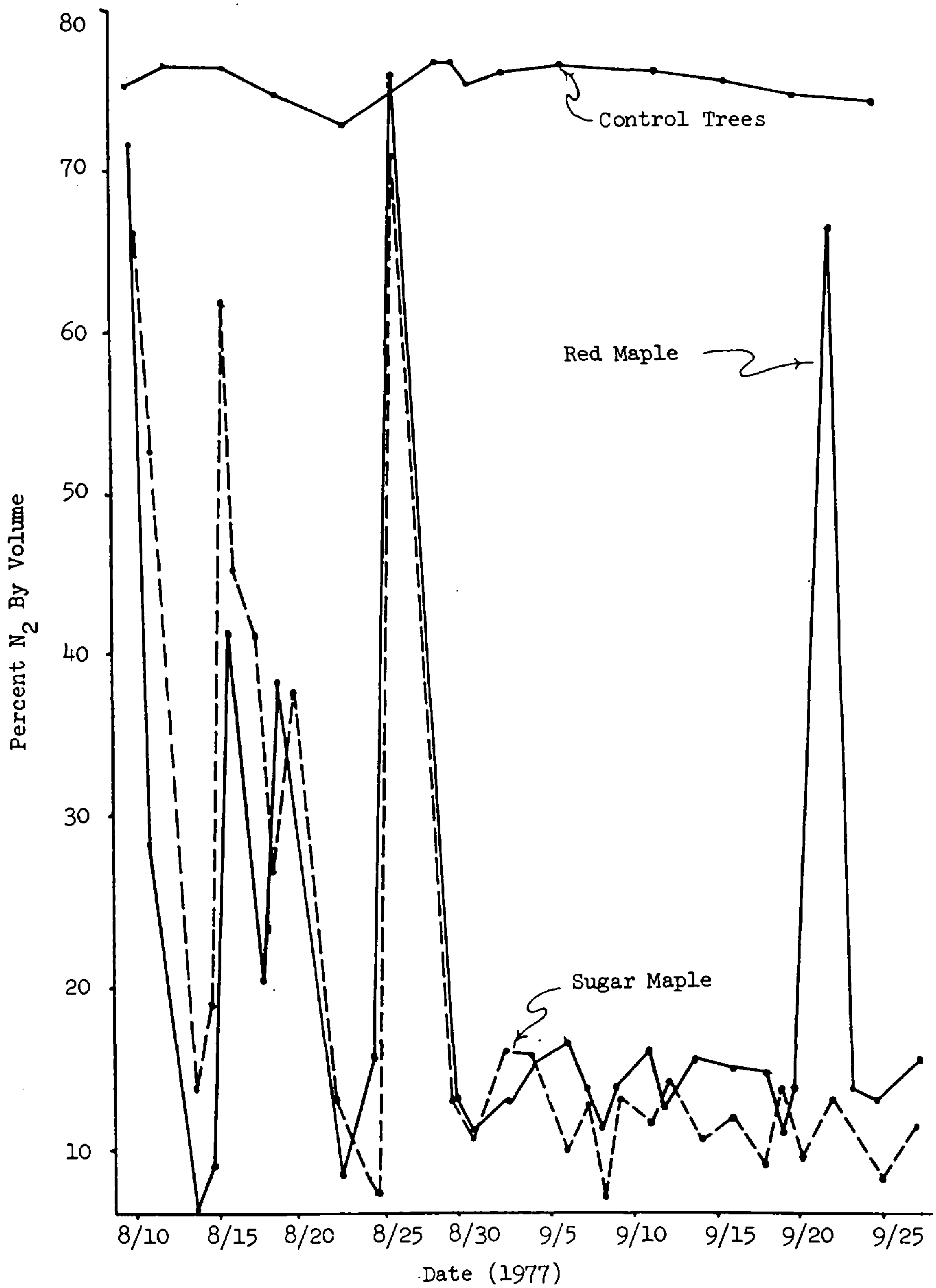


Figure 23. Mean percent N_2 at 7" depth in fumigated trash cans.

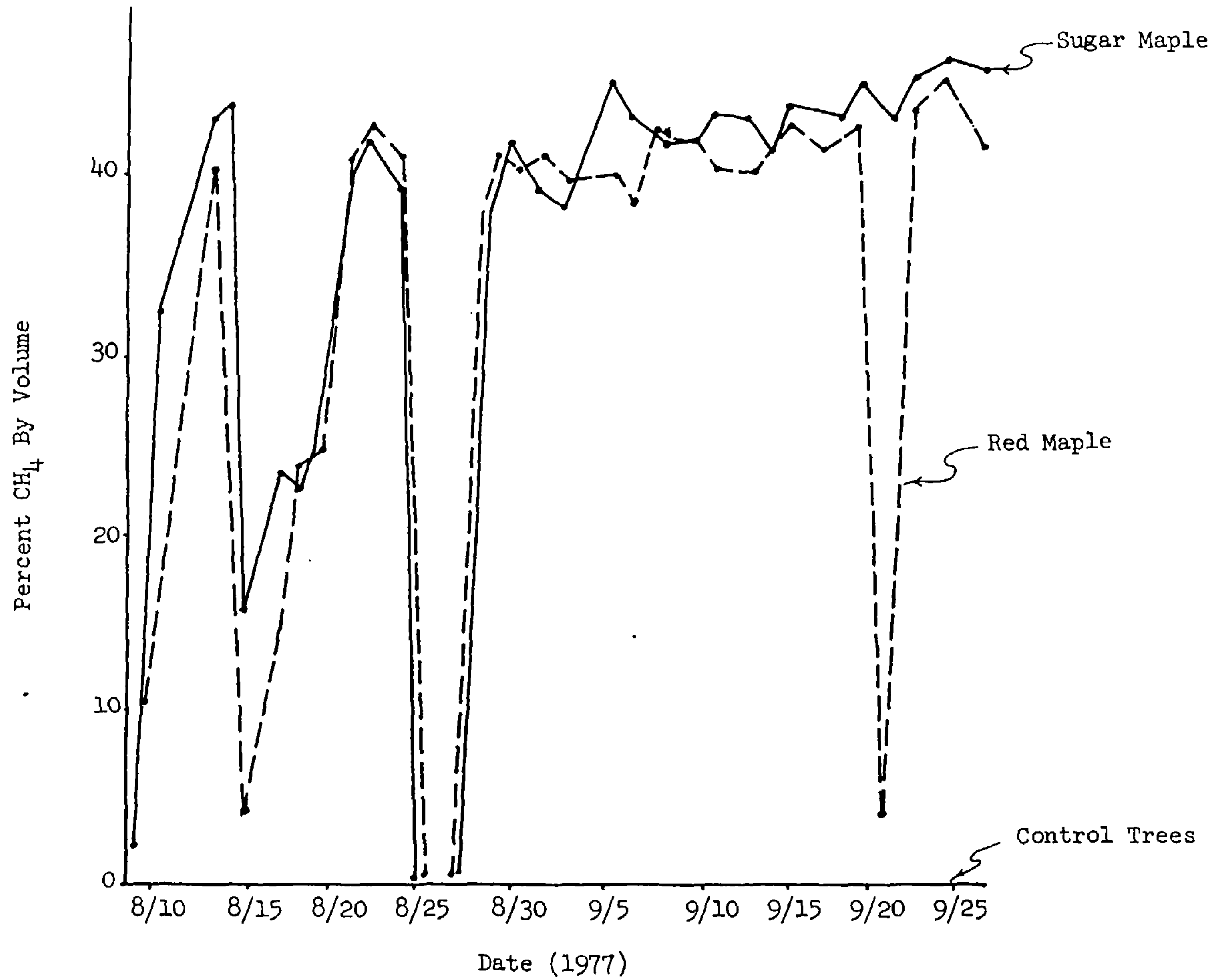


Figure 24. Mean percent CH_4 at 7" depth in fumigated trash cans.

TABLE 39. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT, AND TOTAL NITROGEN CONTENT OF THE LEAVES OF TOMATO PLANTS* AT THE TERMINATION OF EXPERIMENT 1

	Treatment		
	A	B	C
Total Nitrogen (%)	1.9	1.6	1.9
Total dry weight (g)	13.1	12.4	13.1
Total increase in height (cm)	16.7	10.2	16.7

* Each value is the mean of 7 replicates.

Experiment 2

The average composition of the culture vessel substrate atmospheres for each treatment in the two trials of this experiment are given in Tables 40 and 41.

TABLE 40. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 2, (8-DAY FUMIGATION)

	Treatment				
Gas %	A	B	C	D	E
O_2	20.0	6.9	6.6	6.4	6.3
CO_2	0.6	0.7	34.2	39.5	0.9
N_2	79.4	92.4	59.2	7.6	47.6
CH_4	0.0	0.0	0.0	46.5	45.2

* Mean of 20 to 25 observations, corrected to 100 percent.

TABLE 41. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 2, (12-DAY FUMIGATION)

	Treatment				
Gas %	A	B	C	D	E
O_2	20.0	6.7	6.7	5.2	5.0
CO_2	0.5	0.4	35.1	39.2	1.8
N_2	79.5	92.9	58.2	9.8	49.9
CH_4	0.0	0.0	0.0	45.8	43.3

* Mean of 30 to 33 observations, corrected to 100 percent.

The plants that were treated with air or low O_2, but no CH_4 or CO_2 (Treatments A and B) grew significantly better than did the plants receiving high CO_2 with or without CH_4 (Treatments C and D). This was true for both the 8-day and 12-day trials of the experiment and was evidenced by greater nitrogen content of the leaf tissue, increased height of the plants and greater dry weight of the leaf tissue (Tables 42 and 43). The visual appearance of the plants also bore out this relationship. The plants receiving high concentrations of CO_2 with or without CH_4 (Treatments C and D) began to decline after three days of treatment. The symptoms observed were a swelling of the stem accompanied by the formation of adventitious roots which became more pronounced as the treatments continued. The leaves first became chlorotic, then completely yellow and finally, necrotic. This decline progressed upwards on the stem for the duration of the experiment.

At the termination of the 8-day trial the plants receiving air or low O_2 (Treatments A and B) were in the same condition as the plants receiving CH_4 and no CO_2 (Treatment E). This relationship was evident in terms of the parameters measured and the visual appearance of the plants. During the second trial (12 days) the plants receiving CH_4 and no CO_2 were in the same condition as the plants receiving air or low O_2 after eight days of treatment but by the twelfth day they had gone into a rapid decline. This decline was believed to have been caused by lower O_2 concentrations in the vessels brought about by a build-up of methane-utilizing bacteria in the substrate. The O_2 levels had fallen below 2% in Treatment E after eight days of treatment concomitant with the decline of the plants. Oxygen depletion was not observed in any of the other treatments.

During the first trial the temperatures in the greenhouse ranged from 68°F to 77°F and in the vessels from 70°F to 81°F. During the second trial the temperature in the greenhouse ranged from 75°F to 88°F and in the vessels, from 73°F to 90°F. No consistent temperature differences were observed between the treatments.

TABLE 42. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT, AND TOTAL NITROGEN CONTENT OF THE LEAVES OF TOMATO PLANTS* AFTER 8-DAYS OF FUMIGATION IN EXPERIMENT 2

	Treatment				
	A	B	C	D	E
Total nitrogen (%)	2.1a	1.7b	1.6b	1.5b	2.1a
Total dry weight (g)	8.7a	8.7a	2.7b	3.0b	9.0a
Total increase in height (cm)	16.5a	15.3a	4.1b	4.7b	15.5a

* Mean of 4 replicates.
All values in row followed by an a are greater than values followed by a b. ($P < 0.01$).

TABLE 43. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT, AND TOTAL NITROGEN CONTENT OF THE LEAVES OF TOMATO PLANTS* AFTER 12-DAYS OF FUMIGATION IN EXPERIMENT 2

	Treatment				
	A	B	C	D	E
Total nitrogen (%)	2.58a	2.64a	1.68b	1.89b	1.80b
Total dry weight (g)	9.4a	9.1a	3.8c	2.2c	5.9b
Total increase in height (cm)	20.9a	21.1a	6.0c	5.0c	16.6b

* Mean of 4 replicates.
All values in row followed by an a are greater than values followed by a b or c ($P<0.01$). Values followed by a b are greater than values followed by a c ($P<0.01$).

Experiment 3

The mean percent composition of the culture vessel atmospheres for each treatment is given in Table 44. The plants that were treated with low O_2 and low CO_2 (Treatment A) grew significantly better than the plants given high CO_2 with low O_2 or with high O_2 (Treatments B and C). This relationship was evidenced by dry weight of the leaf tissue, increased height of the plants and adventitious root development (Table 45). Five of the plants receiving high CO_2 (Treatments B and C) wilted after three days exposure, and all but two had recovered from their wilted condition by the fourth day of exposure. Of the two plants which did not recover, one was in Treatment B and one in Treatment C. By the tenth day of exposure all the plants given high CO_2 (Treatments B and C) exhibited adventitious root development on the shoots and a general chlorosis of the leaves. The plants remained in this condition throughout the experiment, exhibiting little additional growth. Adventitious root development was suppressed on the two plants which had wilted.

TABLE 44. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 3

	Treatment		
Gas %	A	B	C
O_2	6.3	17.0	6.0
CO_2	0.3	28.7	28.8
N_2	93.4	54.3	65.2

* Corrected to 100 percent.

TABLE 45. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT AND ADVENTITIOUS ROOT DEVELOPMENT OF TOMATO PLANTS AT THE TERMINATION OF EXPERIMENT 3

	Treatment		
	A	B	C
Total increase in height (cm)	41.3a	2.4b	0.4b
Mean dry weight (g)	9.0a	3.0b	2.5b
Adventitious root development	-	+	+

* All values in row followed by an a are greater than values followed by a b ($P < 0.01$).

Experiment 4

The average composition of the atmospheres in the culture vessels for each treatment is given in Table 46.

The plants that were treated with low O_2 (control) or 10% CO_2 (Treatment A and B) grew significantly better than the plants treated with 20% CO_2 (Treatment C). The latter plants all exhibited adventitious root development and general chlorosis by the seventeenth day of exposure (Table 47). The adventitious root development involved, on the average, the lower 9.5 centimeters of the stem at the termination of the experiment. At the start of the experiment all the plants exhibited an interveinal chlorosis believed to have been caused by lack of light due to extended cloudy weather. By the tenth day of exposure this symptom had begun to subside on control and high CH_4 treated plants (Treatments A and D) but was more pronounced on the plants given 10 and 20% CO_2 (Treatments B and C). This symptom had disappeared from all plants by the seventeenth day of treatment but could have been masked on the plants receiving 20% CO_2 by the total chlorosis observed at this time.

By the seventeenth day of exposure all the plants receiving 50% CH_4 (Treatment D) exhibited adventitious root development involving the lower 28.5 centimeters or so of the stems at the termination of the experiment. These plants also exhibited chlorosis of the lower leaves and epinastic curvature of the lower one-third to one-half of the leaves, not all of which were exhibiting chlorosis. The development of these symptoms occurred concomitantly with the lowering of the O_2 percentage in the root atmospheres (Figure 25) presumably due to the activity of methane-utilizing microorganisms.

TABLE 46. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 4

Gas %	Treatment A	B	C	D
O_2	6.3	17.4	17.1	4.3
CO_2	0.4	9.1	18.0	1.7
N_2	93.3	73.5	64.9	49.6
CH_4	0.0	0.0	0.0	44.4

* Each value is the mean of 12 to 15 observations, corrected to 100 percent.

TABLE 47. TOTAL FOLIAR NITROGEN AND DRY WEIGHT AND INCREASE IN HEIGHT AND ADVENTITIOUS ROOT DEVELOPMENT OF TOMATO PLANTS* AT THE TERMINATION OF EXPERIMENT 4

	Treatment A	Treatment B	Treatment C	Treatment D
Total nitrogen (%)	3.1a	2.5a	2.4a	2.0b
Mean total dry weight (g)	11.0a	9.5a	2.0b	8.5a
Total increase in height (cm)	41.0a	51.3a	3.8c	29.3b
Adventitious root development	-	-	+	+

* Mean of 4 replicates.
All values in a row followed by an a are greater than values followed by a b or c ($P < 0.01$). Values followed by a b are greater than values followed by a c ($P < 0.01$).

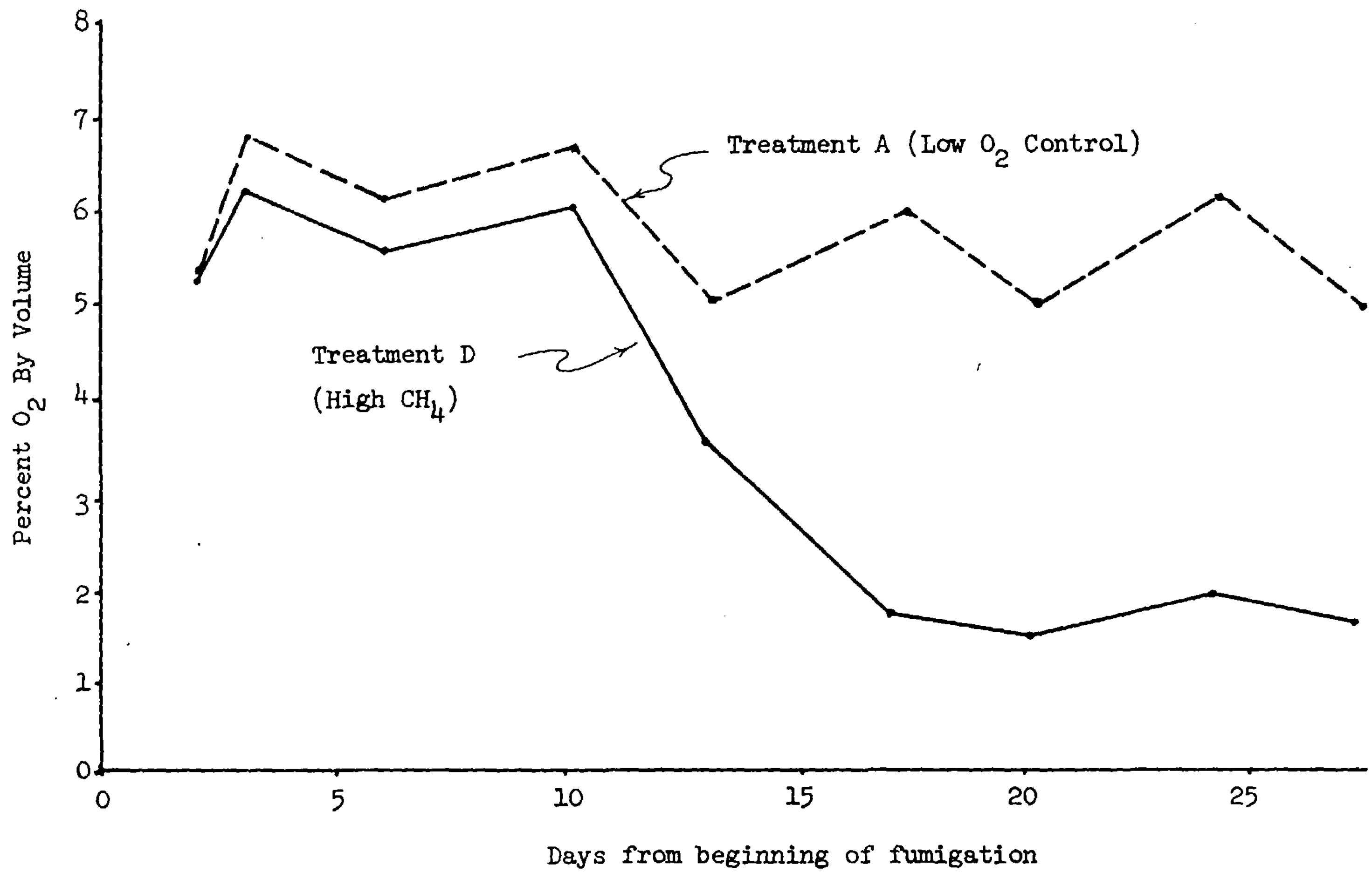


Figure 25. Percent oxygen in culture vessels in tomato Treatments A and D (Experiment 4).

SECTION 7

DISCUSSION

A survey of soil atmospheres on twenty completed sanitary landfills throughout the United States revealed that combustible gas (methane), CO_2 and, to a lesser degree, O_2 readings were concentrated in two extreme percentage categories rather than being evenly distributed among all of the categories (Tables 12, 13, and 14). The combustible gas readings were most extreme in this respect, with 86.2% of the samples containing less than 10% combustible gas by volume, whereas 12.3% of the samples contained 25% or more combustible gas and only 1.4% of the samples had combustible gas concentrations between 10 and 24.9%. This polarization of sample distribution is probably due to the tendency of refuse-generated gas to well up in specific areas rather than uniformly over the entire landfill site. This could be due to the fact that certain areas on the landfill are less restrictive of gas flow and act as chimneys for gas release, or to some characteristic of the refuse. This tendency of gas to occur in isolated areas in the cover material could be useful when vegetating these sites. By locating the areas where the gases are present, high concentrations can be avoided and the loss of expensive trees and shrubs can be minimized.

Data for soil gas composition on the Edgeboro Landfill indicated a strong correlation between the presence of landfill gases in the soil and the poor growth of existing vegetation. The gas samples were taken from a depth near or below the interface between the refuse and the cover material. This indicates that the presence or absence of landfill gases in the cover material was not a function of the depth of the cover but rather a function of the state of decomposition or some other characteristic of the refuse. The tendency of areas of soil covers saturated with landfill gases to be thinner than areas which did not contain landfill gases could be due to soil erosion brought about by lack of protective vegetation over the gas-saturated areas.

The Edgeboro data also indicate that severe contamination of the soil atmosphere by landfill gases was localized and stable on the undisturbed surface of the landfill during the fifteen month period of soil atmospheric sampling. The large size of some of the existing trees in the areas containing little or no soil landfill gas indicates that these areas have probably been stable with respect to gas contamination for a number of years.

A considerable amount of effort and money could be saved when vegetating this or any former landfill where high concentrations of landfill gases are found to occur in the soil cover by not planting at these locations.

Most of the tree deaths on the Edgeboro experimental screening areas can be attributed to factors other than landfill gas (especially on the control). Low soil moisture, transplanting difficulties, animal damage and winter injury can explain many of the deaths.

Rhododendron suffered the greatest number of deaths all of which were attributable to lack of soil moisture or winter injury. Several of these on the experimental plot had landfill gas in the root zone, however, the gas was only detected after these rhododendrons had died. The demise of eight of the ten dead hybrid poplars can also be attributed to lack of soil moisture. These trees, six on the experimental and two on the control, had succumbed during the driest part of the summer of 1977 when the soil moisture reached 5.5% on the experimental plot and 6.0% on the control. No other species appeared to be as adversely affected by the low soil moisture as were these two.

Since black gum and sweet gum had been grown in containers in the nursery, their root systems were rather small at the time of planting, resulting in the death of several replicates of each species on the experimental plot due to lack of water. One replicate of each succumbed on the control plot, also from low soil moisture.

Damage to several euonymus trees by rabbits resulted in severe cambial disruption causing the death of five replicates on the experimental plot and poor growth of most of the others on the experimental and control plots.

The species which were very tall (12-15') at the time of planting (i.e. American sycamore, weeping willow and green ash) suffered from acute water deficiencies on the experimental plot apparently due to their large size. Many American sycamore and weeping willow trees died back and sprouted from the lower trunk and root collar during the first growing season (1976), whereas those on the control plot grew normally and suffered very little dieback.

Although landfill gas was not significantly correlated with death of trees, in a number of instances the carbon dioxide concentration at one foot beneath a recently dead Norway spruce was 18% and under a dead sweet gum 10%. On the other hand, landfill gases were consistently associated with death of trees in one landfill gas-barrier technique where carbon dioxide and methane were much higher than in the landfill screening area. Apparently, gas concentrations in most locations on the screening area were not high enough to cause tree death.

Although landfill gas concentrations in the experimental plot were not high enough to account for actual death of many of the plants, they were of adequate magnitude to detect the order of relative tolerance of the surviving trees as listed in Table 25. This listing resulted from a consideration of four tree variables including leaf and root biomass, shoot length (1976 and 1977) basal stem area.

It is interesting that of the nine most tolerant species, only three i.e. black gum, bayberry and pin oak, (73) have been reported to be able to withstand low oxygen tension in the soil, one of the criteria for selecting experimental species (Table 3). However, seven of these most tolerant species were three feet or less in height when planted, whereas seven of the last ten species in Table 25 were six feet or taller when planted. Obviously, the size of the tree as well as the biological ability of species to withstand low oxygen is important in selecting vegetation for completed sanitary landfills.

In order to assess the role of the various soil variables in predisposing these species to landfill tolerance, multiple regression analysis was performed for data from American basswood (the species present in both types of experiments) for the four tree variables (shoot length, leaf weight, root biomass, basal area). Results indicated that the soil variables, including oxygen, carbon dioxide, temperature, moisture content and bulk density explained a significant portion (95% C.L.) of the variability in the tree responses to landfill conditions. Examination of the quadratic effects of these variables did not result in an increase in the coefficients of determination (R^2); however, when the interactive and reciprocal effects were added to the models, the interactions: moisture content with carbon dioxide, and bulk density with carbon dioxide, as well as the reciprocal of carbon dioxide to the fourth power resulted in a significant increase in the coefficient of determination above that for the linear model.

Regression equations were computed for each of the four variables with respect to American basswood. The equation for shoot length (equation 2, page 84) indicates that the significant soil variables which explain 53% of the variability are carbon dioxide, temperature, bulk density, oxygen and moisture content. The negative coefficients for the first three soil variables indicate that high levels of these variables are correlated with a decrease in shoot length of American basswood trees while the positive coefficients for oxygen and moisture content correspond to an enhancement of growth at high levels and a detrimental effect at lower levels of oxygen and moisture content.

In that the reciprocal and interactive effects of the soil variables increased the R^2 value by 22% for leaf biomass, they were included in the final regression model for leaf biomass (see equation 4, page 85). The significant independent variables temperature, bulk density, the interaction of moisture content with carbon dioxide and the reciprocal of carbon dioxide to the fourth power explained 63% of the variability. High levels of all these variables correspond to a decrease in leaf biomass in that the regression coefficients are negative. The interaction of moisture content with carbon dioxide shows that for the same concentration of carbon dioxide, the leaf weight of basswood is different for different levels of moisture content. The reciprocal effect of carbon dioxide illustrates that at low carbon dioxide concentrations, a small increase in concentration corresponds to a large decrease in leaf weight, whereas at higher carbon dioxide levels, leaf weight changes very little with changes in carbon dioxide concentration.

Thirty-nine percent of the variability in root biomass can be attributed to the soil variables temperature, bulk density and moisture content leaving a considerable amount of the variability unexplained. In that the variance in the root biomass among basswood trees is large compared to the variance among the screening areas and the gas-barrier techniques, it is not surprising that only a small portion of the variability could be accounted for by the independent soil variables. The large variance among trees can be partially explained by the sampling method. The method of sampling roots for the present study, i.e. taking only one sample per tree, is subject to a large amount of error in that the likelihood of collecting widely different biomass for trees growing under the same conditions is high. This stems from the fact that one sample collected from a particular tree may have purely by chance, been taken from a portion of the root system high in root biomass while a sample from another tree may have come from an area of low biomass. This problem can be partially overcome by sampling roots from two or more areas around a particular tree.

The significant effects in the equation describing the basal stem cross-sectional area response of American basswood, with an R^2 of fifty-three percent, were bulk density, the interaction of bulk density with carbon dioxide, and the reciprocal of carbon dioxide to the fourth power. Since the regression coefficient for each of these effects was negative, an increase in the value for these significant soil variables corresponds to a decrease in the basal area. The significant interaction effect illustrates that at a particular level of carbon dioxide, the difference in basal area is not the same for different levels of bulk density. The significant reciprocal effect for carbon diocide shows that a low CO_2 concentration (i.e. 0-5%), a small increase in concentration results in a large decrease in the basal area, whereas at higher concentration (i.e. 5-30% CO_2), an increase in carbon dioxide corresponds with a small decrease in basal area. Rajappan (120) has shown that root growth of red kidney bean was completely inhibited at carbon dioxide concentrations of 5.5%. On the other hand, cotton seedlings grown in hydroponic solution were able to make optimum growth with 10% carbon dioxide present, provided at least 7.5% oxygen was present (52).

Apparently, the variability within each basswood tree for shoot length and leaf weight has been provided for adequately by collecting six and four measurements per tree respectively, because the variance of these two variables for a particular tree is small compared with the variance among trees. Consequently, the R^2 values for shoot length (53%) and leaf weight (63%) are considerably higher than that for root biomass (39%) where one sample per tree was collected.

In that there is only one measurement possible for the cross-sectional basal area of a particular tree, its value should represent very well the amount of growth which that particular tree has produced. However, since the calculation of cross section basal area is dependent upon the tree diameter, then any error in the diameter measurement would result in an erroneous basal area. Furthermore, when the diameter measurement is used for the calculation of basal area, a circular cross section is assumed. This is indeed an invalid assumption in that several of the trees are obviously not circular. Despite the high R^2 value (53%) for basal area of American basswood, some of the unexplained variability can most likely be attributed to the non-circularity of some of the trees.

Despite the correlation of carbon dioxide with the growth of American basswood, higher R^2 values may be obtainable by placing the soil gas collection samplers at a depth comparable to the depth of the root system. This depth was found to be approximately six inches on the experimental plot and eight inches on the control plot. For the present study, gas samplers were twelve inches below the soil surface. Since the average root depth was four to six inches above the depth of the samplers, the gas concentration in the root zone was not precisely measured. However, since carbon dioxide correlates so well with poor growth, apparently the carbon dioxide at twelve inches was related to the concentration in which the roots were growing.

Until now, oxygen has not been considered in the discussion of soil factors and their effect on tree growth since oxygen became a significant effect in only one of the four descriptive equations. The values for oxygen correlated very highly ($r = -.938$) with those for carbon dioxide. Since carbon dioxide was slightly better correlated with growth than oxygen, it was entered into the majority of the equations and oxygen was omitted. However, the absence of oxygen in the equation describing the variability in growth must be interpreted with care. Since it is impossible to describe the effects of each of these gases separately any discussion of the effects of high carbon dioxide concentration on growth is confounded with the effects of low oxygen.

Methane gas concentrations on the experimental plot screening area averaged approximately one percent of the soil gas atmosphere at a depth of one foot. Since this concentration is low, methane was not a significant factor in explaining the variability in the tree responses. The low methane concentration may be due to the action of Pseudomonas chromobacterium in the landfill cover soil which utilizes methane as a source of carbon in its metabolism (70). Oxygen is also required during the metabolism of these bacteria which ultimately produce carbon dioxide and release it to the surrounding soil. Therefore, the action of these bacteria in the landfill cover-soil results in the production of carbon dioxide at the expense of oxygen and methane. This reaction may be significant in that our studies indicate that methane is innocuous to tomato plants if oxygen is not limiting, whereas carbon dioxide has a detrimental effect on growth. If activity of these bacteria can be inhibited, then less carbon dioxide will be present in the landfill soil and the vegetation growing in this soil may have a better chance to survive.

The nature of the soil strata (i.e. consisting of ten year old refuse lying beneath two feet of soil) and perhaps the higher soil temperatures and sand content on the experimental landfill plot helped promote drying of the soil. Normal capillary water movement is restricted in such a soil structure to the top two-feet enabling the roots to obtain additional water only from irrigation or rainfall, and not from deeper soil layers. The soil structure on the control plot is closer to normal with two feet of soil spread over virgin land. Here, capillary action can help supply water to the roots under low moisture conditions. In addition, the slope of the experimental plot was about two percent whereas that of the control was one percent, promoting more runoff on the experimental plot and resulting in less water percolation and ultimately a lower soil moisture content. If the rate of transpiration is measured on both plots for particular species along with soil moisture content through time, rate of soil moisture loss relative to the transpiration rate can be calculated for both plots. If these rates are proportional on the control plot and not proportional on the experimental plot, then some of the water was perhaps lost from the experimental plot soil by processes other than transpiration.

This could imply one of two processes: first, that more water is percolating through the two-foot soil layer on the experimental plot and being lost to the refuse layer below and that on the control plot the undisturbed soil beneath the top two feet is slowing down percolation; second, that on the control plot, the deeper soil permits capillary water movement upwards toward the dryer surface layer where the roots are located and that on the experimental plot where only two feet of soil lies above thirty feet of refuse, these deeper soil layers are not present to facilitate such capillary action. Further studies may show whether or not these relationships are valid.

The trees on the control plot produced more leaf biomass than those on the experimental plot, causing more of the smaller trees and shrubs as well as the soil to be shaded to a greater extent on the control plot. This may have tended to reduce the transpiration rate of the shaded plants and thus the rate of evaporation from the soil surface to lessen the water demand on the control plot. In that soil moisture content has contributed significantly to explaining the variability in equations two (page 84) and five (page 85) let us examine it further.

The experimental plot was also more exposed to the elements and more likely to be subjected to stronger winds than the control. This could place an even greater demand fôr water on the trees growing in the experimental plot so that the evapotranspiration rate would be enhanced at the expense of soil moisture and may further explain the significantly lower soil moisture on the experimental plot.

The direct relationship of soil moisture content with plant response is brought out by the positive regression coefficients for moisture content in equations two and five showing that when moisture content was increased, the American basswood trees responded by increasing growth. Although this relationship is significant when all the American basswood data is included in the analysis, where moisture content was highest (in clay/vents trench), the growth of basswood was the poorest, i.e. the reverse of the previously stated relationship. This supports the positive relationship between growth and soil moisture content in that the regression coefficient is positive, despite the reverse relationship in the clay/vents trench.

Why then is the high moisture content in the clay/vents trench associated with the poorest growth? To answer this question it is necessary to recall that water is one of the products of decomposition of the organic matter in refuse (21). In addition it is also produced by the methane-utilizing bacteria (70). It travels along with the other decompositional gases and since both carbon dioxide and methane were high in this trench, presumably the high moisture content resulted from water vapor migrating with these decomposition gases. The carbon dioxide concentration was a significant factor in the regression equation calculated for shoot length, leaf weight and basal area for American basswood and had a negative coefficient, illustrating the detrimental effect of carbon dioxide on American basswood growth. Therefore, the high carbon dioxide in the clay/vents trench appeared to have contributed largely to the poor growth of these trees despite the high moisture content.

Lack of soil moisture might have had an effect not only in reducing water uptake by plants on the experimental plot and ultimately reducing productivity, but also by reducing the assimilation of very soluble nutrients such as nitrogen. Although the leaf tissue was not analyzed for nutrient content during the present study, future analysis will make possible a better understanding of the effects of landfill soil environment on nutrient uptake and assimilation.

The soil nutrient levels were also found to be influenced by the landfill environment. The ratio of $NO_3^-:NH_4^+$ on the experimental and control screening areas were identical following the application of fertilizer in the spring of 1977; however, by November of 1977, the $NO_3^-:NH_4^+$ ratio on the control was more than two times greater and significantly different from the ratio on the experimental plot indicating one or both of two things: either more ammonium nitrogen was converted to nitrate on the control plot because of the higher oxygen concentration in the soil on the control plot, or nitrate on the experimental plot was reduced to ammonium due to the utilization of the oxygen portion of nitrate in the metabolism of soil bacteria (117). This reduced the amount of nitrate in the soil and could result in a lower $NO_3^-:NH_4^+$ ratio as exhibited on the experimental plot.

The $NO_3^-:NH_4^+$ ratio in the clay/vents trench where the oxygen concentration was 4.3%, was more than two times less than the other gas-barrier techniques where the oxygen was 16.3% or greater. The same two possibilities as described above most probably contributed to these phenomena.

The manganese content in the experimental and control screening areas as well as in six of the seven gas-barrier techniques averaged approximately 10 ppm. However, in the clay/vents trench, where the oxygen concentration averaged 4.3%, the manganese reached 45 ppm. These relationships indicated that at oxygen concentrations of 17.8% (i.e. on the experimental screening area), free manganese does not increase in the soil. However, when the average oxygen concentration is 4.3% (i.e. in the clay/vents trench) then manganese is significantly increased in the soil. Manganese available to plants is reportedly significantly increased in soils flooded for short periods of time (117).

Considering the nutrient changes described above, it is apparent that at oxygen concentration of 17.8% on the experimental plot, a slight reduction in the ratio of nitrate to ammonium nitrogen is occurring (Table 8) compared to the control where the oxygen concentration is 19.7% and that when the oxygen concentration reaches 4.3% (in clay/vents trench), oxides of manganese are also reduced, increasing the free manganese in the soil (Table 33).

Because the pH of the soil in the clay/vents trench was very low

(5.0) the high manganese content may have been toxic to the plants in the trench and contributed to their demise. One recommendation to help lower the availability of manganese is to lime the soil, thereby raising the pH and decreasing the likelihood of manganese toxicity to plants.

The effectiveness of each gas-barrier technique in preventing methane gas migration into the trenches may be evaluated by considering the ratio between the methane concentrations around the periphery of the trench and those inside the trench. In the gravel/plastic/vents trench and clay barrier trench, the ratios are 207:1 and 54:1 respectively, indicating that these trenches have functioned effectively in keeping out methane gas. On the other hand, for the clay/vents trench, the 1:1 ratio indicated that this gas-barrier technique was not effective in preventing the migration of methane from the refuse into the trench.

No gas measurements were made in the soil immediately adjacent to either of the two mounds on the experimental plot. However, methane or elevated carbon dioxide levels were never detected in either mound. Furthermore, the average carbon dioxide concentration on the experimental screening area surrounding these mounds was six percent indicating that both mounds functioned successfully in preventing gas migration.

Interpreting the effectiveness of each gas-barrier technique is not as straightforward as it may first appear. Despite the previously presented ratios between gas outside and gas inside the trenches, the concentrations below the trenches were not measured and may differ from one trench to another. In addition there is no way to determine if the clay barrier below the clay/vents trench has remained intact. Although there are not obvious signs of refuse settlement around this trench, small amounts of settlement may have split the clay barrier allowing the upward movement of gases into the soil in the trench. This might explain the high methane and carbon dioxide in this trench. Future experiments with gas-barrier techniques should include more than one application of each technique in order to make adequate assessment of effectiveness in preventing gas migration. In this study only one replicate of each technique was employed.

Another way of assessing the effectiveness of each barrier technique was by the growth of the two species in each of these areas. For the same three techniques which prevented landfill gas from contaminating the soil, analysis of variance showed growth of American basswood significantly greater (99% C.L.) than the experimental screening area which acted as the control for the barrier techniques. Because of the large variability in growth responses of Japanese yew within each technique no significant differences were found between the techniques and the experimental screening area for this species. Presumably, the great variability in Japanese yew growth was partially due to planting only four replicates per technique instead of six as were planted for American basswood.

Carbon dioxide contamination in the root zone of tomato plants in solution culture was toxic when the concentration of CO_2 averaged 17.0% during the experimental period. When CO_2 concentrations averaged 8.8% or less no symptoms were observed, indicating that there was a threshold level between

9 and 17% at which CO_2 became toxic under these experimental conditions. Tomato plants exposed to 17% CO_2 exhibited progressive chlorosis and abscission of the lower leaves, adventitious root development, swelling of the stem near the nodes, chlorosis of the entire plant, and a reduction in the growth rate. Complete symptom development was observed on all plants by the 17th day of fumigation. Exposing tomato roots to concentrations of CO_2 between 25 and 36% resulted in earlier and more severe symptom development on tomato plants than did 17% CO_2. These higher CO_2 concentrations caused some of the plants to wilt after only three days of fumigation, and some plants never recovered. The other symptoms were fully expressed on all plants given 26 to 27% CO_2 by the tenth day of fumigation and on plants given 34 to 38% CO_2 by the eighth day of fumigation.

These findings are consistent with what is reported in the literature. Erickson (44) in 1946 found that 28% CO_2 in the root zone severely reduced the growth rate of tomato plants. The symptom development observed in this experiment was also similar to that observed by Erickson on plants exposed to low O_2 and/or high CO_2 in the root medium. This type of symptom development was also reported by Jackson (75) in 1948 and Kramer (84) in 1951, on tomato plants grown in poorly aerated growth media.

No interaction was observed among O_2, CO_2 and CH_4 when they occurred together in the root zone in terms of symptom development on tomato plants. When the CO_2 was held at 27%, O_2 at either 5.5 or 16% caused no differences in symptom development. Plants exposed to 34 to 38% CO_2 alone exhibited the same symptom development as plants exposed to 34 to 38% CO_2 with 43% CH_4.

Exposing the roots of tomato plants to 43% CH_4 for an 8-day period resulted in no measurable adverse effects, whereas a 12-day exposure resulted in a decline of the tomato plants concomitant with a decrease in O_2 concentration in the culture vessels. This decrease in O_2 is believed to be due to the activity of methane-utilizing microorganisms. Hoeks (70) in 1970 also reported that exposing soil to high concentrations of CH_4 resulted in eutrophication by the second week of exposure.

Tomato plants are known to be sensitive to poor soil aeration and will exhibit characteristic symptoms when so exposed (44, 75, 84). These symptoms include: adventitious root development, swelling of the stem near the nodes, progressive chlorosis and abscission of the lower leaves, reduction in growth and an epinastic curvature of the leaf petioles. Such symptoms were duplicated exactly when the O_2 concentrations decreased in the cultures fumigated with 43% CH_4. However, the plants exposed to high concentrations of CO_2 exhibited less extensive adventitious root development, less swelling of the stem and little or no epinastic curvature. Chlorosis often involved the entire plant rather than just the lower leaves, and in some cases the entire plant wilted after only a few days of exposure. This indicates that CO_2 may damage tomato plants by means of a mechanism different from that through which low O_2 concentrations in the root zone causes plant damage.

Sugar maple was intolerant of flooding as evidenced by the statistically significant decrease in transpiration rate after only one day of flooding and the loss of all leaves by the termination of the experiment. Red maple seedlings were more tolerant of flooding than were more tolerant of flooding than were sugar maples, their transpiration rate did not decrease until the 42nd day of flooding and this decrease was not statistically significant. The lower half of the leaves on the flooded red maples were chlorotic by the end of the experiment but this did not influence the stomatal diffusion because the porometer readings were taken only on the uppermost leaves. The fact that red maple is more tolerant of flooding than sugar maple has been reported in the literature (61).

Flood tolerance has been attributed to more than one adaptive mechanism in several species (72). The adventitious root development and swelling of lenticels observed on the flooded red maples in this experiment have been found to occur on many other "flood tolerant" species and are believed to contribute to flood tolerance to some degree. Such morphological adaptations were not observed on the red maples fumigated with simulated sanitary landfill gas mixtures. This is not surprising since adventitious root development is dependent upon the presence of water and lenticel opening requires high humidity near the stem. Other adaptations which are believed to contribute to flood tolerance which are not as water dependent include the ability to withstand elevated levels of CO_2 in the soil (72) and to undergo anaerobic root respiration without the production of inhibitory concentrations of ethanol. Mechanisms such as these could explain why the differences between the two species were more pronounced in their response to flooding than to soil contamination with simulated landfill gas. The inability to develop adventitious roots and to permit opening of the lenticels in response to landfill gas contamination would reduce the advantage enjoyed by flood tolerant species, whereas, other mechanisms contributing to flood tolerance such as the ability to withstand elevated levels of CO_2 in the soil or undergo anaerobic respiration in the roots which are not inhibited by lack of water and would continue to supply some protection.

Considering these factors, red maple might be a better choice as a tree to plant on a completed sanitary landfill than sugar maple. The ability to withstand flooding might be a good characteristic for a tree to have since uneven settlement of the refuse can wreak havoc with surface drainage, creating ephemeral ponds. The greater ability of red maple than sugar maple to withstand the presence of CO_2 and CH_4 in the soil was not as dramatic as the ability to withstand flooding. Being less sensitive to these gases red maple could develop a more extensive root system giving it a competitive advantage over sugar maple whose root development would be more likely to be inhibited by high CO_2 and CH_4 in the soil.

SECTION 8

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15. SUPPLEMENTARY NOTES

Robert E. Landreth, Project Officer 513/684-7871

16. ABSTRACT

A study was undertaken to determine which tree species can best maintain themselves in a landfill environment; to investigate the feasibility of preventing landfill gas from penetrating the root zone of selected species by using gas-barrier techniques; and to identify the (those) factor(s) which are most important in maintaining adequate plant growth on completed sanitary landfills. Ten replicates of nineteen woody species were planted on a ten-year old completed sanitary landfill and five gas-barrier systems were constructed. Of the nineteen species planted on the landfill black gum proved most tolerant and honey locust least tolerant to anaerobic landfill conditions. Of the five gas-barrier systems tested, three proved effective in preventing penetration of gas into the root systems of the test species. Investigations into the effects of CO_2 and CH_4 contaminated soil indicated that red maple is more tolerant to the presence of these gases than is sugar maple.

An investigation of the effects of carbon dioxide (CO_2) and/or methane (CH_4) contaminated soil atmospheres on the growth of tomato plants indicated that CO_2 was toxic to tomato roots in a low O_2 soil atmosphere, whereas CH_4 was innocuous under the same conditions. No interaction was observed between CO_2 and CH_4 in terms of damage to tomato plants.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Effect of Vegetation on Landfill Stabilization

by Fred J. Molz[a] and V. Douglas Browning[a]

ABSTRACT

Six types of vegetation were established successfully on lysimeters containing sanitary landfill materials. The vegetation grew well with the roots penetrating several refuse layers within one year. Leachate analysis indicated that vegetation and evapotranspiration (ET) reduced leachate volume and increased the rate of refuse decomposition. This was accompanied by production of a more potent leachate and a substantial increase in cumulative chemical oxygen demand. Therefore, this study suggests more potential ground-water pollution in a shorter period of time when vegetation is planted on a landfill. The net effect of ET on the stabilization of any particular landfill will be the result of a complex interaction involving climate, vegetation, soil type, cover material, landfill geometry, and other variables. This makes extrapolation of our results to a particular field situation rather difficult.

INTRODUCTION

Presently, sanitary landfills are among the most feasible alternatives for disposing of the nation's solid waste. According to Vardy (1974), they will likely remain so at least through 1990. However, the concept of what a sanitary landfill should be has changed greatly during the past two decades and will continue to evolve during the remainder of this century.

The major environmental problems associated with landfills derive from leachate production, gas generation, and vectors (Steiner, *et al.*, 1971). In early landfills, which were often simply open dumps, these problems were largely neglected. Presently, however, landfills are located and/or managed so that leachate, gas, and vector problems are kept within reasonable bounds (Giddings, 1977). This has led to the use of impervious barriers, underdrains, gas vents, leachate recycling, and leachate treatment (Salvato, *et al.*, 1971; Pavoni, *et al.*, 1973; Cook and Foree, 1974; Ho, *et al.*, 1974; Van Fleet, *et al.*, 1974; Norstedt, *et al.*, 1975; Chian and Dewalle, 1976).

The amount of water available for leachate production can be decreased by removing it from the landfill directly through evaporation and transpiration (Molz, *et al.*, 1974). Evaporation will proceed naturally and can help to reduce leachate volume (Caffrey and Ham, 1974). However, a dense stand of vegetation must be established to maximize water removal through transpiration. Many landfill operators establish vegetation for aesthetic, erosion control, and other reasons (Flower, 1976; Lee, *et al.*, 1976). Nevertheless, the effect of vegetation on refuse decomposition is largely unknown. In this paper, we examine the possibility of using vegetation to influence the stabilization process of a landfill. (By stabilization process, we mean the process by which a landfill decomposes and ultimately becomes an inert material.)

DESCRIPTION OF EXPERIMENTS

To study the effects of vegetation on sanitary landfills and vice versa, we performed two sets of experiments. One experiment dealt with problems related to root growth in sanitary landfill materials and results are reported elsewhere (Browning, *et al.*, 1978). The second experiment, reported here, is

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Discussion open until May 1, 1978.

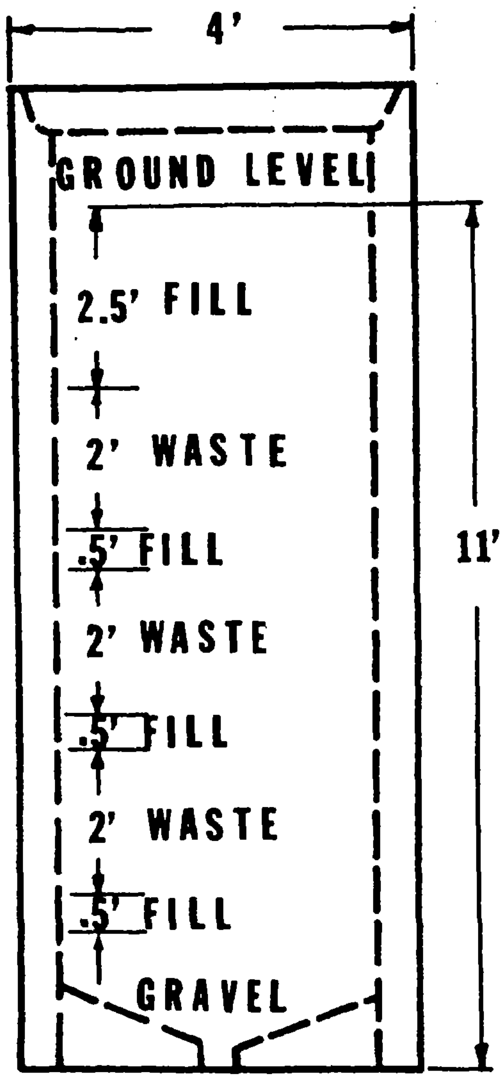

Fig. 1. Diagram showing the manner in which refuse and cover material were placed in the full-scale lysimeters. The base of the lysimeter was connected to a drain.

concerned with the effect of evapotranspiration (ET) on leachate quantity and quality and on landfill stabilization rate. Three full-scale and three half-scale lysimeters were constructed, as shown in Figures 1 and 2. The full-scale lysimeters were constructed of commercially available concrete drain pipe. Two six-foot sections were sealed together with epoxy and rubber strips so that each lysimeter could be filled with water without leaking. The half-scale lysimeters were constructed of stainless steel with one glass wall to aid observation of root growth. The solid-waste mixture, whose composition is listed in Table 1, was weighed out, mixed thoroughly, and placed in the three half-scale, rectangular lysimeters (Bell, 1964), while a representative sample of municipal waste from the Auburn sanitary landfill was placed in the three full-scale, cylindrical lysimeters. The fill and cover soil was a gray-brown sandy loam with a pH of 5.9. All six lysimeters were exposed to the natural climate and constructed so that no runoff could occur. On the rare occasions when supplemental watering was necessary, it was applied equally to each lysimeter.

Leachate quantity and quality were measured each month on the full-scale lysimeters, which were equipped with drain systems and placed on a concrete slab. Samples were taken from each lysimeter, refrigerated, and analyzed. Leachate was allowed to drain freely from the half-scale lysimeters, which were constructed so that gas could be sampled at any depth. Four sets of gas samples were taken during the course of the experiments. All six lysimeters were equipped with thermistors, so that temperature could be recorded as a function of depth and time. Leachate quality measurements included chemical oxygen demand, total Kjeldahl nitrogen, and total solids. They were made using Standard Methods (1976).

Because our major objective was to study the effect of vegetation on refuse decomposition, we established various types of vegetation on four of

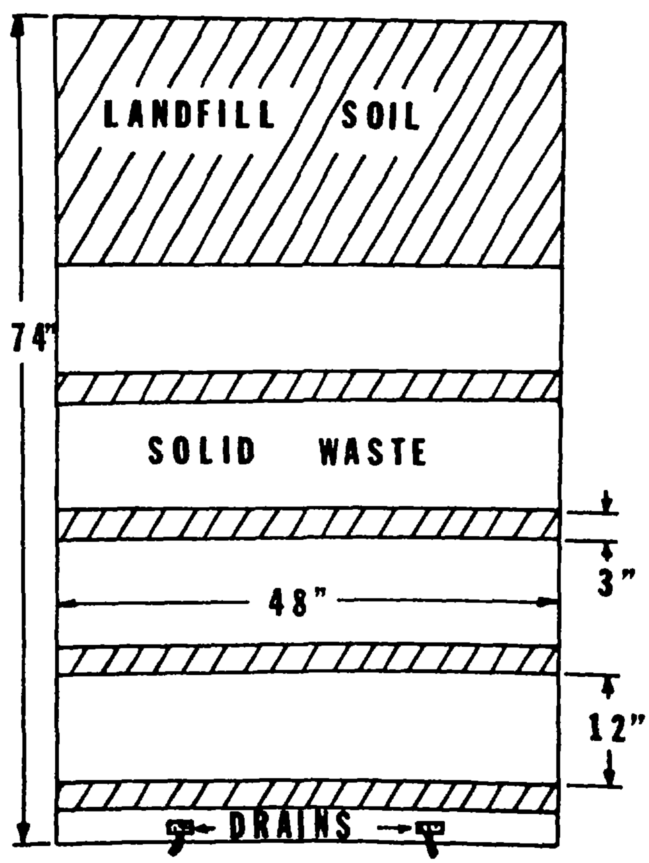

Fig. 2. Side view of a half-scale lysimeter showing the soil and refuse layers as first placed. After placement considerable settlement occurred. One wall of the half-scale lysimeters was made of glass so that root growth could be observed.

Table 1. Physical Constituents of Solid Materials Used in Half-Scale Experiments
[100 lb (454 Kg) Sample of Municipal Refuse]

Type	*Wet Wt (lbs)*	*Dry Wt (lbs)*	*Moisture (lbs)*
Combustibles:			
Paper	48.0 (21.8 Kg)	35.0 (15.9 Kg)	13.0 (5.9 Kg)
Garbage	16.0 (7.3 Kg)	8.0 (3.6 Kg)	8.0 (3.6 Kg)
Leaves & Grass	9.0 (4.1 Kg)	5.0 (2.3 Kg)	4.0 (1.8 Kg)
Wood	2.0 (0.9 Kg)	1.5 (0.7 Kg)	0.5 (0.2 Kg)
Synthetics	2.0 (0.9 Kg)	2.0 (0.9 Kg)	0.0 (0.0 Kg)
Cloth	1.0 (0.5 Kg)	0.5 (0.2 Kg)	0.5 (0.2 Kg)
Total	78.0 (35.4 Kg)	52.0 (23.6 Kg)	26.0 (11.8 Kg)
Noncombustibles:			
Glass	6.0 (2.7 Kg)	6.0 (2.7 Kg)	0.0 (0.0 Kg)
Metal	8.0 (3.6 Kg)	8.0 (3.6 Kg)	0.0 (0.0 Kg)
Other*	8.0 (3.6 Kg)	6.0 (2.7 Kg)	2.0 (0.9 Kg)
Total	22.0 (10.0 Kg)	20.0 (9.1 Kg)	2.0 (0.9 Kg)

* Ashes, stone, dust, etc.

the six lysimeters. Lysimeter I (Figure 1) was planted with 3 black locust *(Robinia pseudoacacia* L.), 4 brisley locust (*Robinia hispida* L.), Italian rye grass (*Lolium multiflorum* Lam.) and goosegrass (*Eleusine indica* L. gaertn). Lysimeter II was planted with 1 slash pine (*Pinus caribaea* morelet) and 1 thorny elaeagnus (*Elaeagnus pungens* L.). Lysimeter III was kept devoid of vegetation (fallow) and used as a control.

For the three half-scale lysimeters (Figure 2), lysimeter No. 1 was planted with 5 slash pines and goosegrass, the second kept fallow for control purposes, and the third planted with 1 thorny elaeagnus and goosegrass. All lysimeters received identical amounts of water due to rainfall and a little supplemental watering during the first few weeks after planting.

RESULTS OF EXPERIMENTS

All species of selected plants grew reasonably well. The slash pine thrived throughout the year, while during the wet seasons, the thorny elaeagnus yellowed and dropped some of its leaves. The locust trees seemed healthy but did not grow as well as six controls planted nearby on the ground surface. All grasses grew very well and seemed unaffected by their environments.

Figure 3 shows the type of gas profile to which the roots in the half-scale lysimeters were subjected. (Gas samples were not taken from the full-scale lysimeters.) The oxygen (O_2) level was relatively high down to the first refuse layer, which was due to diffusion down from the soil surface because the lysimeter walls were airtight. Below the first layer, O_2 concentrations were low and CO_2 concentrations were relatively high. Very small amounts (1 percent or less) of a gas were detected that presumably were methane (CH_4). Nevertheless, pine tree roots penetrated to the bottom of the half-scale lysimeters within ten months after planting. This rather high rate of depth penetration may have been induced by the lateral confinement of the lysimeter walls.

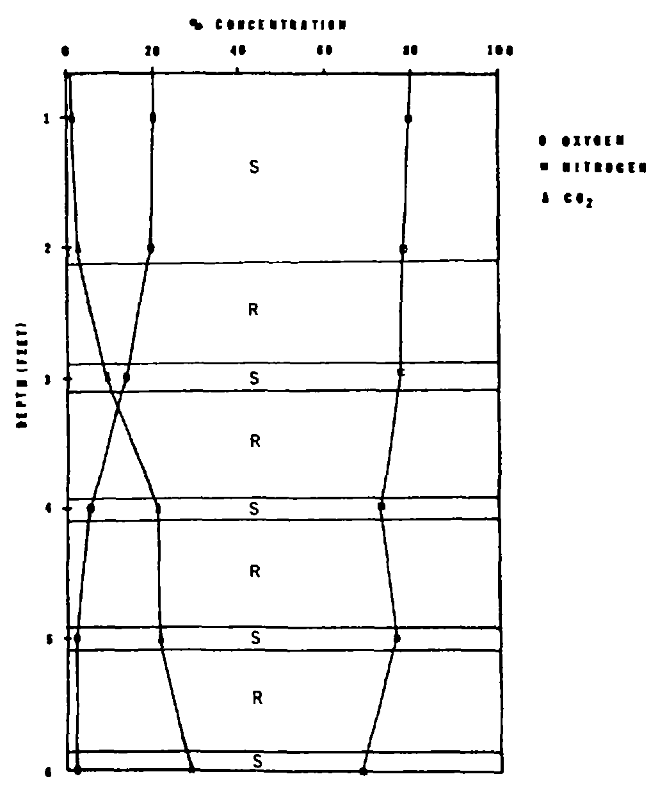

Fig. 3. Typical gas profiles measured in one of the vegetated half-scale lysimeters using a chromatograph. Each point resulted from one measurement. The respective layers are labeled "S" for soil and "R" for refuse.

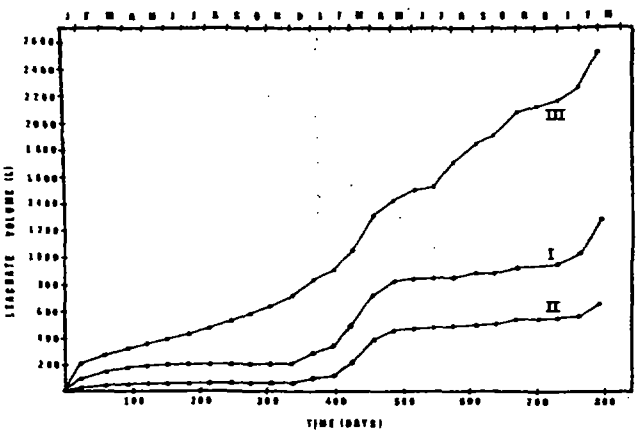

Fig. 4. Cumulative leachate volume (liters) as a function of time for the three full-scale lysimeters.

Figure 4 shows the leachate volumes produced by the three full-scale lysimeters as a function of time. Leachate flow began during January 1974, about seven months after the lysimeters were filled. As expected, fallow lysimeter III produced the greatest leachate volume whereas lysimeter I containing the locust produced an intermediate volume. Lysimeter II, vegetated with pine and elaeagnus, produced the minimum. This is consistent with the fact that the pine and elaeagnus were green all year and produced relatively heavy foliage, while the two locust plants dropped their leaves in the winter, thereby preventing leaf transpiration.

For the vegetated lysimeters, little or no leachate was produced during the late spring, summer, and early fall months (Figure 4). For this period, ET equaled or exceeded the precipitation. During the late fall, winter, and early spring, precipitation exceeded ET, the entire soil-refuse profile reached field capacity, and appreciable leachate was produced. The leachate production pattern for the fallow lysimeter was quite different (Figure 4). Water content of the soil and refuse increased steadily until field capacity was reached. Thereafter, leachate was produced at about the same rate as precipitation less soil evaporation. Thus, the parts of the vegetated lysimeters affected by plant roots were subjected annually to a cyclic wetting and drying, while the fallow lysimeter reached field capacity and remained in that condition except for the top 8 cm (3.15 in) of soil cover.

Figures 5, 6, and 7 show chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and total solids (TS), respectively, as functions of time for the full-scale lysimeters. The COD, TKN, and TS values from the vegetated lysimeters were typical of values obtained by other investigators. Cook and Foree (1974) obtained a leachate with a COD of 17,500 mg/l (ppm) and a TKN of 220 mg/l (ppm), while Boyle and Ham (1974) obtained a leachate from the City of Madison (Wisconsin) Refuse Reduction Demonstration Project with a COD of about 11,000 mg/l (ppm). The COD obtained from fallow lysimeter III was somewhat low, but the TKN and TS were typical. The most

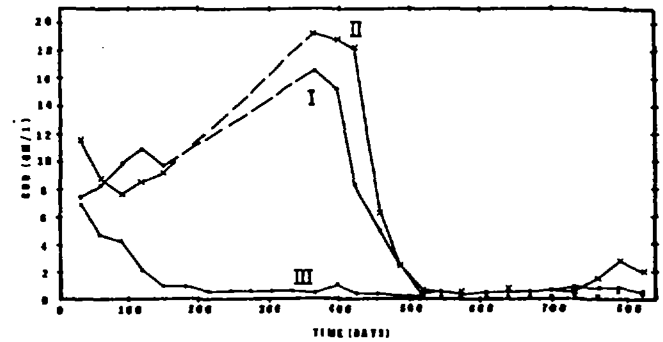

Fig. 5. Chemical oxygen demand (grams/liter) as a function of time for the three full-scale lysimeters. The dashed lines indicate periods of zero leachate production or missing data.

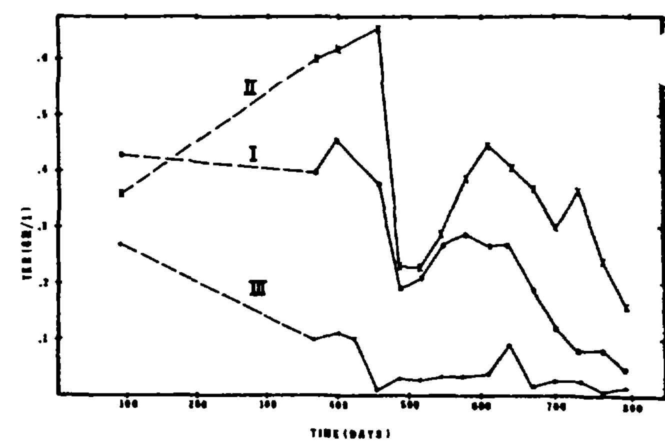

Fig. 6. Total *Kjeldahl* nitrogen (grams/liter) as a function of time for the three full-scale lysimeters. The dashed lines indicate periods of zero leachate production or missing data.

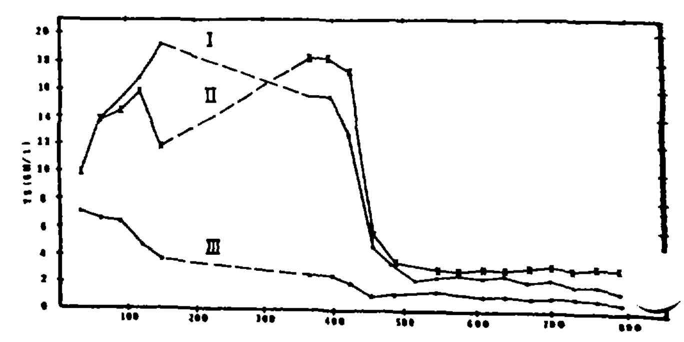

Fig. 7. Total solids (grams/liter) as a function of time for the three full-scale lysimeters. The dashed lines indicate periods of zero leachate production or missing data.

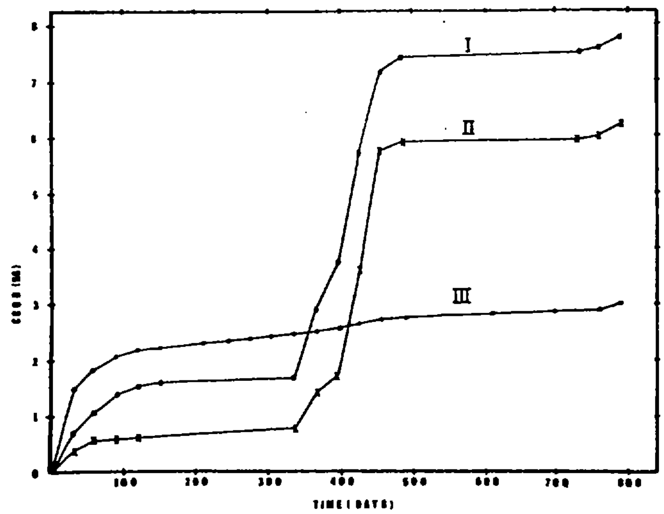

Fig. 8. Cumulative chemical oxygen demand (kilograms) as a function of time for the three full-scale lysimeters.

remarkable aspect of the three figures is the distinct difference between the vegetated and unvegetated lysimeters. For every leachate quality measure, fallow lysimeter III produced a less potent leachate. Also, the COD, TKN, and TS for lysimeter III tended to decrease steadily with time, while the vegetated lysimeters produced more COD, TKN, and TS during the cold and wet season when precipitation exceeded ET. This is somewhat similar to the result noted by Rovers and Farquhar (1973).

During the study period, the decrease in leachate volume for vegetated lysimeters I and II (Figure 4) was not sufficient to compensate for the increased leachate potency indicated in Figures 5, 6, and 7. For COD, the net result of these two effects is shown in Figure 8, which presents a plot of cumulative chemical oxygen demand (CCOD) as a function of time. Over the 800-day leachate-production period, the vegetated lysimeters produced more total COD even though they had lower volumes of leachate.

DISCUSSION

Generally, a more rapid rate of refuse decomposition produces a more potent leachate as reflected by COD, TKN, TS and other quality measures (Caffrey and Ham, 1974). Therefore, the results shown in Figures 5 through 8 seem to indicate that the refuse in the vegetated lysimeters was decomposing more rapidly than that in the fallow lysimeter. In order to test this hypothesis as directly as possible, we dismantled the half-scale lysimeters during November 1975 to determine the dry weight of the partly decomposed refuse in the several layers. This measurement was meaningful since each half-scale lysimeter had been filled with identical types and volumes of solid-waste mixtures (Table 1).

Results of our dry weight measurements, made 33 months after the solid waste had been covered, are shown in Table 2. Undoubtedly, refuse in the fallow half-scale lysimeter was decomposing more slowly than that in the vegetated half-scale lysimeters. In the fallow lysimeter, ferrous metals were much less rusted and newspapers could be read easily. Corresponding material in the vegetated lysimeters was highly decomposed. Thus, the cyclic wetting and drying, to which the upper portions of the vegetated lysimeters were subjected, was more conducive to refuse decomposition than was the static, field capacity condition of the fallow lysimeters.

With the half-scale lysimeters, the whole profile was dried substantially by ET during the late spring, summer and early fall months. This would result in much more O_2 diffusing to the refuse layers from the soil surface. At least during these seasons, the refuse would be undergoing appreciable amounts of aerobic decomposition (Caffrey and Ham, 1974; Rovers and Farquhar, 1973). The increased decomposition rate, due to partial aerobic conditions, most likely explains a large part of the decreased dry weight shown in Table 2.

For the full-scale lysimeters, increased O_2 would not be expected to have as large an effect on the increased mass and depth of refuse. When we dismantled lysimeter II, containing the pine and elaeagnus, in November, 1976, we found relatively little root growth at the lower levels, and many of these roots seemed to have recently died. [This might have indicated that roots

Table 2. Dry Weight of Refuse Remaining in the Top Two Layers of the Half-Scale Experiments After 33 Months*

Lysimeter	*Layer 1*	*Layer 2*
No. 1 (Pine)	28.94 lbs (13.13 Kg)	–
No. 2 (Fallow)	77.38 lbs (35.10 Kg)	53.60 lbs (24.31 Kg)
No. 3 (Elaeagnus)	35.50 lbs (16.10 Kg)	35.75 lbs (16.22 Kg)

* The initial weight per layer was 108 lbs (49 Kg).

advanced during favorable (dry) conditions and died back during unfavorable (wet, more anaerobic) conditions in a yearly cycle.] Thus, a smaller fraction of the refuse in the full-scale lysimeters would be supplied with increased O_2 as compared with that in the half-scale lysimeters. This was consistent with visual observations of the refuse layers in lysimeter II. Only the top layer seemed relatively decomposed. Because the products of oxidation are relatively mild, aerobic decomposition alone would not be expected to produce a more potent leachate as indicated in Figures 5, 6 and 7. Thus, even though the dry weight measurements made on the half-scale lysimeters and the leachate quality measurements made on the full-scale lysimeters both indicate more rapid refuse decomposition under vegetated conditions, a more detailed thought analysis suggests that there is at least a possibility that different decomposition processes were operating in the two cases.

As pointed out by Caffrey and Ham (1974), the optimum water content for producing a high rate of anaerobic decomposition ranges from 60 percent of dry weight to complete saturation. The presence of vegetation may have induced a water content distribution more conducive to anaerobic activity in at least a portion of the full-scale lysimeters. This, and possible synergistic interactions between aerobic and anaerobic activity, could explain the increased production of COD by the vegetated lysimeters noted in Figure 8. However, more research is needed to be certain of the explanation.

SUMMARY AND CONCLUSIONS

Several types of vegetation, including black locust, brisley locust, slash pine, thorny elaeagnus, Italian rye, and goosegrass were established successfully on lysimeters containing sanitary landfill materials. The vegetation grew well, especially the pine, even though the decomposition in the lower two-thirds of the lysimeters became mildly anaerobic. Within ten months of planting, the pine roots had penetrated to the bottom of the six-foot (1.83 M) half-scale lysimeters. When the full-scale lysimeters were dismantled, pine roots were found at the 12-foot (3.66 M) level that had died recently. From this, we inferred that pine roots penetrated the full depth during dry periods, but then died back during wet periods when the soil and refuse was at field capacity or saturated and more anaerobic conditions existed.

From measurements made on the full-scale lysimeters, we concluded that the early effect of vegetation and ET was to reduce leachate volume considerably and to increase the rate of refuse decomposition. This was accompanied by production of a more potent leachate and a substantial, short-term increase in net pollution. Except for the reduction of leachate volume, further study is needed to extrapolate our results to a field situation with certainty, even qualitatively. For example, anaerobic activity, when it developed, appeared to be relatively mild in our experiments as compared to field situations (Flower, personal communication). The net effect of ET on the stabilization of any particular landfill will be the result of a complex interaction between climate, vegetation, soil types, cover material, landfill geometry, and other variables. However, the effect of growing selected vegetation on landfills is substantial and, therefore, this practice is potentially useful as a landfill management tool.

ACKNOWLEDGMENTS

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Objectives of NWWA

The objectives of this association shall be: to assist, promote, encourage, and support the interests and welfare of the water well industry in all of its phases; to foster, aid and promote scientific education, standards, research, and techniques in order to improve methods of well construction and development, and to advance the science of ground-water hydrology; to promote harmony and cooperation between well contractors and scientific agencies relative to the proper development and protection of underground - water supplies; to encourage cooperation of all interested groups relative to the improvement of drilling and pumping equipment; to encourage, serve, assist and promote closer cooperation among the existing State water well contractors' associations and to foster the development of such associations in States where they do not exist; to collect, analyze, and disseminate to the public facts about the role of the water well industry in the economy of the nation; and to advance generally the mutual interests of all those engaged in the water well industry, in their own and the public welfare.

NWWA Constitution

Modelling the mechanism of wind-induced damage on Scots pine

Heli Peltola

Background to the study. The frequency of strong winds has increased since the early 1960s especially during unfrozen soil conditions in Finland. This is assumed to be related to changing climatic conditions. At the same time, the structure of the forest ecosystem has become more prone to wind damage; e.g. because of increasing thinning intensities and the preference given to clear felling. This structural change in the forest ecosystem, combined with the increasing frequency of strong winds, especially during those months of the year when the soil is unfrozen, could substantially increase timber losses in the future. Furthermore, the more humid and warmer weather pattern expected in the future is also expected to increase the risk of windthrow for treesbecause of reduced soil freezing, which until now has enhanced trees' anchorage from late autumn up to the early spring, during the most windy months of the year. In this context, this subproject was aimed at studying the mechanism of wind induced damage on Scots pine (*Pinus sylvestris* L.), i.e. by developing (i) a simulation model for the mechanism of windthrow and stem breakage of Scots pines in stand edge conditions (for static wind load), by studying (ii) tree swaying as caused by dynamic wind loading in field conditions, by studying (iii) the risk of windthrow for Scots pine in terms of the turning moment caused by dynamic wind loads along the margins of clear-felled areas using a model approach, and by outlining (iv) the implications of the occurrence of soil frost and its depth in forest soils, as modified by the warming climate, and consequent increase of the risk of windthrows due to changes in tree anchorage.

Material and methods. Within the scope of this subproject, a mechanistic model for wind damage of Scots pine was developed in orderto fully describe the mechanistic behaviour of trees exposed to wind loading. The model developed was aimed at determining the windspeed required to uproot single trees or to break tree stems. The model is theoretical and based on the physical properties of trees and vertical wind profiles along stand edges (Peltola and Kellomäki 1993, Peltola 1995).

Tree swaying caused by dynamic wind loading was also studied along the edge of a stand of Scots pine as well as within the stand by means of two field experiments (Peltola et al. 1993, Peltola 1995, 1996a). Wind and tree swaying measurements (i.e. mean wind profiles and stem displacement measurements) made along the edge of a stand of Scots pine (Peltola et al. 1993) were used especially in validating the simulation model thus developed (Peltola and Kellomäki 1993). Wind and tree swaying measurements conducted both along the stand edge and a distance of two tree heights into a stand of Scots pine, before and after the first thinning (2700 and 1500 stems per ha), concentrated on the relationship between windspeed and the resulting stem displacement using spectral analysis technique (Peltola 1995, 1996a).

This subproject also involved model computations in order to evaluate the risk of windthrow of Scots pine along the margins of clearfelled areas by evaluating this risk in terms of the turning moment arising from the dynamic wind load (Peltola 1995, 1996b). The turbulent wind field across the forest clearing and within the stands at the clearing margins was simulated using a two-dimensional model developed elsewhere (see Peltola 1996b).

Furthermore, the impacts of frost decrease in forest soils on the risk of windthrow was also evaluated in a stand of Scots pine bothin southern Finland (Helsinki region) and in northern Finland (Rovaniemi region), respectively (Peltola et al. 1996a). Soil frost was simulated using the FinnFor model developed by Kellomäki et al. (1993) and it was compared to current windspeed statistics available for the period 1961-1990. In frost simulations, the present mean annual temperature was assumed to increase by 2-4oC.

Results. In a tree swaying study (Peltola 1995, 1996a), it was found that nearly equal wind energy transfer and damping of the system occurs between the two stand densities studied. However, a clear difference was observed between trees located along the stand edge and those located within the stand. This means that trees growing along the stand edge (and especially along a newly cut edge) are more liable to wind loading than trees within the stand. On the other hand, with respect to the stand densities studied, neither were trees along the stand edge very likely to be damaged.

According to computations made using a mechanistic wind damage model developed within this subproject by Peltola and Kellomäki (1993), the windspeed required to blow down a tree or break the stem of a tree located along the stand edge decreased if the height to diameter ratio or the crown to stem weight ratio of the trees increased (as well as when the tree size increased). The windspeed required to uproot a tree was much smaller than that required to cause the stem to break. On the other hand, even windspeeds of 12-14 ms-1 were found to be strong enough to uproot Scots pines (slender individuals) located along the stand edge (Peltola and Kellomäki 1993).

In addition, based on the model computations by Peltola (1995, 1996b), stand density and height were found to affect mostly the windspeed and turning moment on trees located along the stand edge, i.e. it decreased as stand density increased and increased as stand height increased. Thus, the risk of uprooting increases also sharply with increasing tree height and the differences between various stand densities increases also along with height increase. On the other hand, the difference in windspeed between various clearings of different sizes (0.04-4.0 ha) was only some percent for the same stand height and stand density along the stand edge. However, the turning moment decreased quite substantially when the distance from the stand edge increased, and the decrease was greatest at the dense margin and within the distance of one tree height from the edge into the stand (30%). According to the results obtained in this study (Peltola 1995, 1996b), the risk of uprooting might be even greater for trees at the margins of smaller clearings, because of the much greater length of perimeter at risk.

Until now, frozen soil has increased trees' anchorage during the time of year usually characterised by strong winds, i.e. from late autumn to early spring. In the future, especially in southern Finland, the duration of soil frost may decrease from 4-5 months down to 2-3 months, if 2-4oC is added to the present mean annual temperature (Peltola et al. 1996a). Furthermore, it seems that the number of days when the soil is frozen may decrease substantially more in the deeper soil layers (40-60 cm) than near the ground surface (0-20 cm), especially in southern Finland. Similarly, in northern Finland, the number of months when the soil is frozen may decrease from 5-6 months down to 4-5 months (Fig. 9). In northern Finland, the same kind of dramatic change in the number of days when the soil is frozen as in southern Finland is not evident, not even in deeper soil layers. On the whole, the improved stability of forest trees from late autumn to early spring due to soil frost may substantially decrease in the future, thereby evidently increasing the risk of windthrow. This is because the number of strong winds during in unfrozen soil conditions seems to substantially increase. Nowadays, up to 45 % of the strong winds occur during months when the soil is frozen (i.e. >15 days per month when soil frost occurs in soil layers of 0-40 cm) in southern Finland, whereas in the future this percentage is expected to be only ca. 20 %. In northern Finland, the corresponding percentage of days today is 60 %, and in the future 50 %.

Discussion of results. A more humid and warmer weather pattern than today can make Scots pines (as well as other tree species), and especially in southern Finland, far more liable to windthrow during winter and spring storms than is the case nowadays because of a substantial decrease in soil frost and thus of weakening of the anchorage to the soil of trees. This risk will be even more evident especially if the air temperature during winter months increases by as much as 6-8oC, as has been suggested, thereby further decreasing the occurrence of soil frost. Furthermore, changing climate may also increase the frequency (as well as intensity) of storm activity in northern latitudes and increase the risk of wind-induced damage even more than can be expected based on the current wind climate.

In the future, the mechanistic wind damage model(Peltola and Kellomäki 1993, Peltola 1995, Peltola et al. 1996b) developed within this subproject can, for example, be used to study how thinning intensity and its timing affect critical windspeeds under various stand conditions. The model will also be applicable to tree species other than Scots pine (e.g. Norway spruce and birch species) with different tree, stand and site characteristics applying to trees located along the stand edge as well as within the stand, through the modification of the controlling equations and parameters.In addition to wind loading, the model can also be used to determine the snow load required to damage single trees. The model will be validated by tree pullings (static force) made mostly in the autumn of 1995 and windspeed profile and tree swaying measurements from the years 1991-1996.

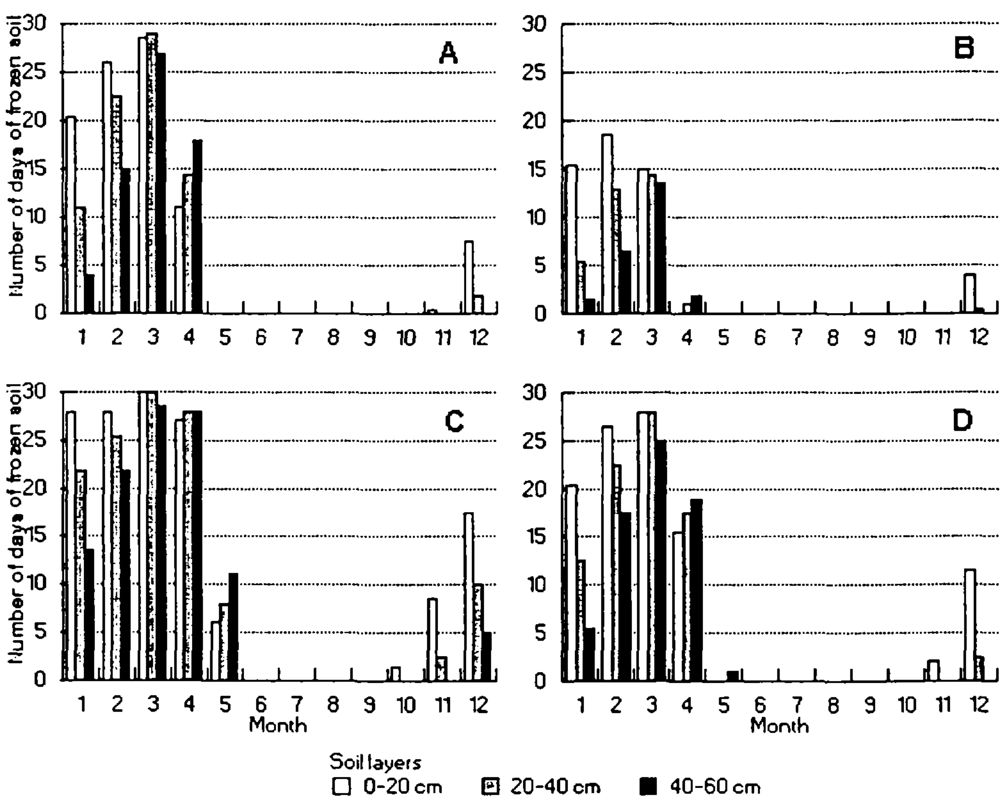

Fig. 9. Number of days with frozen soil conditions at Helsinki for various soil layers for [A] current temperature conditions (1960-1990), [B] when temperature has elevated +4 degrees, and [C] and [D] at Rovaniemi, respectively.

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:nowledgements

. Croft for rainfall and drainage measurements; ;es, G. J. Smith for ^{36}Cl counting and to the : for computing facilities, also A. J. Thomasson 1 re characteristic profile.

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SHRINKAGE IN CLAYEY SUBSOILS OF CONTRASTING STRUCTURE

M. J. REEVE and D. G. M. HALL

(Soil Survey of England and Wales, Shardlow Hall, Shardlow, Derby DE7 2GN)

Summary

Shrinkage was measured on subsoil samples from two clayey alluvial soils of contrasting structural development and two boulder clay soils also of contrasting structure. Of the four phases of shrinkage recognized, the proportion of shrinkage attributable to the structural shrinkage phase is shown to be dependent on structural development and organic carbon levels in the subsoil. The importance of structural shrinkage to the maintenance of good structure in clay soils under intensive cultivation is briefly discussed.

Introduction

SUMMER shrinkage and subsequent winter swelling in fine-textured soils is a perennial process, the magnitude of which varies according to soil type, land use and annual climate. Lateral shrinkage, causing cracking in clay soils, is not only important for water entry and movement (Blake *et al.*, 1973; Ritchie and Adams, 1974), and structural development (White, 1966) and regeneration, but in severe cases, can affect the stability of buildings and pavements (McCormack and Wilding, 1975).

The earliest work on soil shrinkage was by Tempany (1917) and Haines (1923) who studied blocks moulded from soil paste. Haines distinguished these main phases: normal, residual and no shrinkage. The first occurs when the change in soil volume equals that of water lost, and residual shrinkage occurs when air enters and reduction in soil volume is less than volume of water lost.

Later work by Lauritzen and Stewart (1941) and Lauritzen (1948) was with natural soil clods where shrinkage was seen to be different from the simple pattern observed by Haines. Lauritzen and Stewart, comparing shrinkage with water retention data, noted that wilting point corresponded to a maximum ratio of volume-change to water loss.

Stirk (1954) defined a fourth phase of shrinkage from experiments with natural clods. Termed structural shrinkage, it has similar characteristics to residual shrinkage (*i.e.* water loss greater than volume change) but occurs at the wet end of the moisture range and is associated with removal of water from coarse pores.

In the two very dry summers of 1975 and 1976, many British soils shrank markedly, and many samples were taken to study the shrinkage characteristics of different soils. The shrinkage characteristics discussed here were chosen to investigate shrinkage mechanisms under different structural conditions.

Materials and methods

Soils and sampling

Two pairs of soil series were chosen. In each pair, the soils had similar particle size distributions, bulk density and clay mineralogy class (Avery and Bullock, 1977) throughout their profiles (Table 1), but they differed in degree of structural development in the immediate subsoil. In all four soils, the profile sampled was near the central concept of that soil series.

The Fladbury and Wyre series are both clayey alluvial soils: the former is classified (Avery, 1973) as a pelo-alluvial gley soil and has an horizon assemblage of A, Bg, BCg while the Wyre series is a gleyic brown alluvial soil with A, Bw, Bg, BCg horizons. Both samples were from arable land on alluvium of the River Nene in West Northamptonshire and are described by Reeve (n.d.) The second pair of soils consisted of profiles of the Ragdale and Faulkbourne series (Reeve, n.d.), both sampled on Chalky Boulder Clay under arable land in West Northamptonshire. The Ragdale series is a pelo-stagnogley soil with A, Bg and BCg horizons, and the Faulkbourne is a typical argillic pelosol with A, Bw, Btg and BCg horizons.

The Bg (or Btg) and BCg horizons in all soils generally had prismatic and coarse blocky structures but the Bw horizons in the Wyre and Faulkbourne series had a fine angular blocky structure. Hence, both of these soils can be considered as having a well-developed structure for a clay soil, the Wyre series contrasting with the poorly structured Fladbury series and the Faulkbourne with the poorly-structured Ragdale series.

Sampling was undertaken during early spring when the soils were at or very near to field capacity and fully expanded. Winter sampling was avoided as clays can take two to three months to swell fully after a return to field capacity (Smith, 1973). A pit was dug, the soil profile described to 1 m (Hodgson, 1974), and large clods of soil were taken from each main subsoil horizon. Bulk samples were taken for particle size analysis and clay mineralogy, and cylindrical cores for moisture release and density measurements.

Laboratory methods

Three replicate clods of 100–200 g (50–120 cm^3) were prepared from the large field clods from each main horizon and rewetted on saturated foam to make up for any slight moisture loss during transport to the laboratory. They were then suspended in a cradle of cotton and coated with a 1:5 solution of 'Saran' resin in butanone according to the method of Brasher *et al.* (1966). The Saran coating allows the passage of water vapour during drying and maintains close contact with the clod during shrinkage, but acts as a barrier to liquid water when the volume of the clod is determined by water immersion. The clods were then hung to dry and the mass and volume determined at frequent intervals. When the volume lost between weighings became negligible, the clods were dried at 105°C and re-weighed.

Moisture retention measurements were made on triplicate 222 cm^3 cylindrical cores from each horizon. Samples were equilibrated at 0.05, 0.1 and 0.4 bar suction on sand and kaolin tension tables, and at 2 and 15 bar on a pressure membrane apparatus. The method is described by Hall *et al.* (1977).

Curves relating volume change to water loss were drawn, and water retention values from the cores were related to them, using water content at zero suction as the starting point for the curves. Replicate clod samples from any one horizon generally gave parallel and nearly coincident curves. A typical range in total shrinkage obtained from triplicate samples was 40 ± 1%.

Organic carbon was determined by Tinsley's (1950) wet digestion method and expressed as per cent of oven-dried soil. Particle size distribution was determined by

TABLE 1
Sample data

Soil series and grid ref.	*Horizon*	*Depth of Sample* (cm)	*Fine clay* <0.2 µm (%)	*Clay* <2 µm (%)	*Silt* 2–60 µm (%)	*Organic carbon* (%)	<2 µm *C.E.C.* (me/100 gm)	*Clay mineralogy class*	*Bulk density at fully expanded state* ($g\ cm^{-3}$)	*Structure*
Wyre SP630319	Bw	30–40	24	58	35	2.7	47.0	smectitic	1.08	strong fine angular blocky
	Bg	60–80	25	64	31	1.5	45.8	smectitic	1.13	moderate medium prismatic (breaking to [illegible] lar blocky)
[illegible]	[illegible]	40–50	22	59	26	1.3	59.2	smectitic	1.03	moderate co[illegible]

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TABLE I
Sample data

Soil series and grid ref.	*Horizon*	*Depth of Sample* (cm)	*Fine clay* <0.2 µm (%)	*Clay* <2 µm (%)	*Silt* 2–60 µm (%)	*Organic carbon* (%)	<2 µm C.E.C. (me/100 gm)	*Clay mineralogy class*	*Bulk density at fully expanded state* (g cm⁻³)	*Structure*
Wyre SP630319	Bw	30–40	24	58	35	2.7	47.0	smectitic	1.08	strong fine angular blocky
	Bg	60–80	25	64	31	1.5	45.8	smectitic	1.13	moderate medium prismatic (breaking to angular blocky)
Fladbury SP632620	Bg	40–50	22	59	26	1.3	59.2	smectitic	1.03	moderate coarse angular blocky
Faulkbourne SP665664	Bw	25–35	18	36	33	1.3	46.2	smectitic	1.47	moderate fine angular blocky
	Btg	70–80	21	44	33	0.9	41.1	mixed	1.46	moderate medium prismatic (breaking to angular blocky)
Ragdale SP682629	Bg	40–50	13	44	24	0.7	42.4	mixed	1.48	moderate coarse angular blocky

the pipette method (Avery and Bascomb, 1974) after pre-treatment with hydrogen peroxide to remove organic matter, and dispersion overnight with sodium hexametaphosphate (Calgon). Cation exchange capacity was determined by the method of Bascomb (in Avery and Bascomb, 1974) on <2 μm peroxidized clay separates.

Results and Discussion

Figs 1 and 2 relate volume to moisture content for each of the horizons studied. The volume reduction is expressed as a percentage of that at saturation and moisture content as a percentage of oven-dry mass. The 'zero air voids' line shows the hypothetical relationship of shrinkage to water content if air does not enter the clod, and the vertical distance between the two lines at any point is a measure of air entry. Shrinkage phases have also been added using the limits defined by Stirk (1954), *i.e.* normal shrinkage if the ratio of volume change to water loss is greater than 0.9, residual and structural shrinkage if the volume change ratio is 0.05 to 0.9 and no shrinkage if the ratio is less than 0.05.

The main difference between the two sets of samples is in the total amount of shrinkage and the moisture range over which it occurs. In the Faulkbourne and Ragdale samples total volume reduction is 20–25 per cent occurring over a moisture content range of about 25 per cent. In contrast, the Wyre and Fladbury samples lose 35 to 43 per cent of their initial volume over a moisture content range of about 50 per cent. These basic differences can be related to clay content, clay mineralogy and initial density and will be discussed in a later paper, but the relationship of the different shrinkage phases will be discussed here.

poor clay

In all the samples, the three phases of no shrinkage, residual shrinkage and normal shrinkage are present; the dominance of this last phase, although often associated with slight air entry, does not confirm Lauritzen's (1948) findings that the term 'normal shrinkage' hardly applies to clods. The recognition of a structural shrinkage phase depends on the relationship of clod size to the size of structural aggregates. Clods of 50–120 cm^3 from horizons with coarse structure size were invariably from within a structural aggregate, while those from finely-structured horizons included many structural aggregates and fissures. Hence it is not surprising that structural shrinkage is especially evident in those horizons (*viz.* Faulkbourne and Wyre Bw) in which the ped size is fine and the degree of structural development moderate to strong. The Ragdale sample, for which a structural shrinkage phase cannot be recognized, had a weakly developed coarse structure. These results merely confirm the usefulness of Stirk's term and the suitability of the name chosen for that phase of shrinkage.

Within each set of samples, the moisture range over which structural shrinkage occurs increases with increasing degree of structural development, and curtails the phase of normal shrinkage. However, in each case the greater volume change ratio of the normal phase is reached before a moisture suction of 15 bar is attained, and in the poorly structured samples (*viz.* Fladbury and Ragdale Bg horizons) at much smaller suctions.

In Fig. 3, structure is expressed as a score. A score of one, two or three was given respectively for weak, moderate or strong degree of development and a further score of one, two or three for coarse, medium or fine structure size. Hence total scores ranging from 3 to 6 were arrived at and plotted against total structural shrinkage (measured along the volume reduction axis) expressed as a percentage of

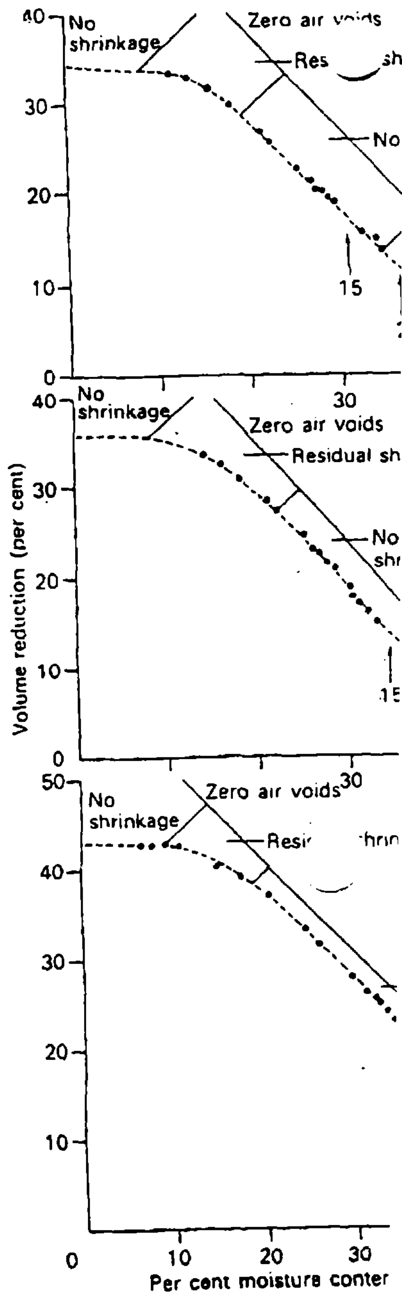

FIG. 1. Shrinkage curves and phases I

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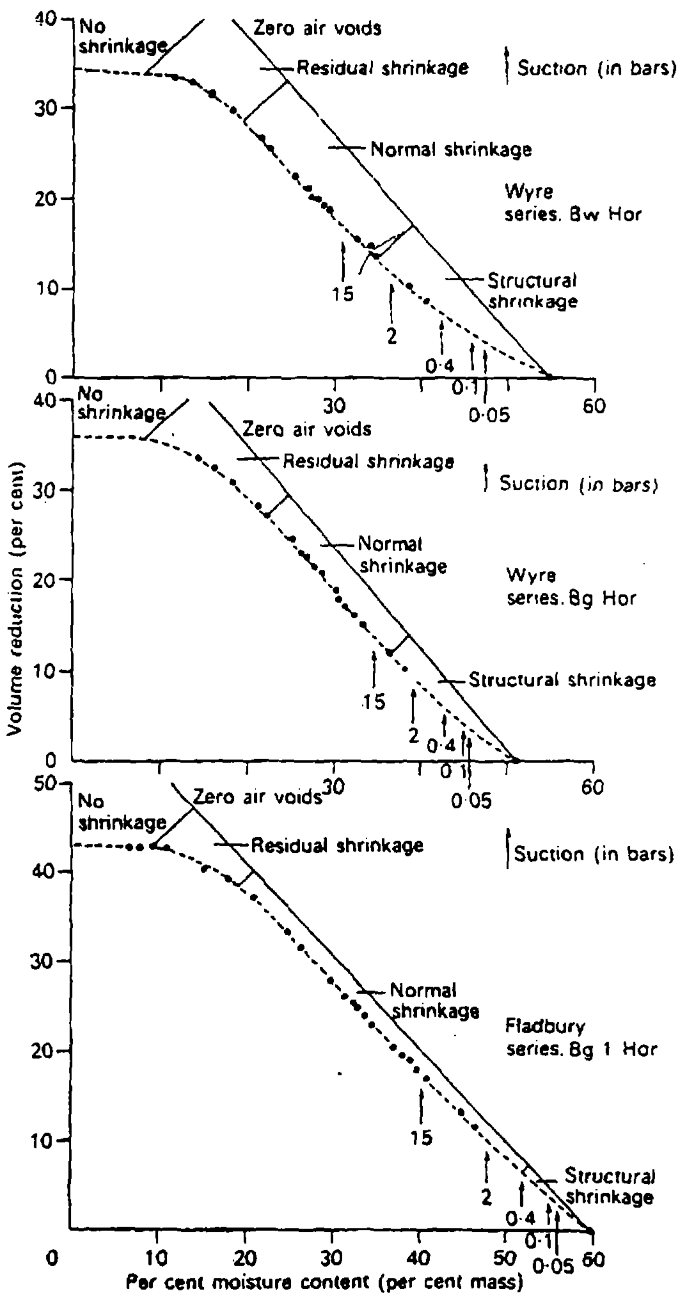

FIG. 1. Shrinkage curves and phases for the Wyre and Fladbury Series.

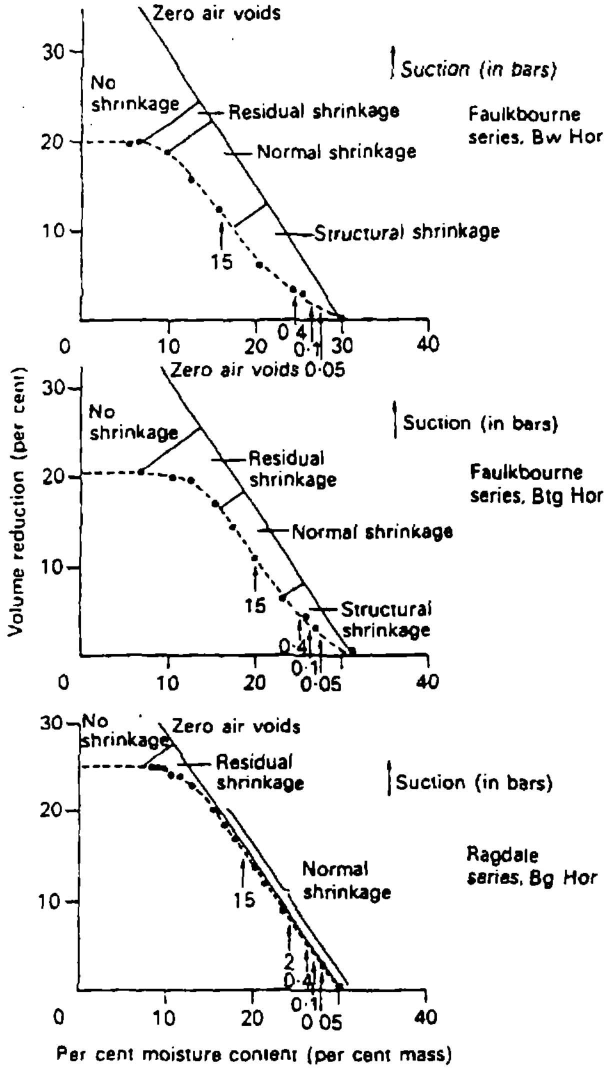

FIG. 2. Shrinkage curves and phases for the Faulkbourne and Ragdale samples.

total shrinkage. The plot confirms the importance of macro-structure in the initial shrinkage phase.

As clay content, clay mineralogy and bulk density are similar within the two sets of samples, the volume of air entering during structural shrinkage must be either related to unquantified chemical differences or to organic carbon content or visible macro-structure. These two variables are partly interdependent as larger organic carbon contents often accompany well structured subsoils. Fig. 4 does indicate a relationship between organic carbon content and total air entry during structural shrinkage. It may be that the organic carbon helps to stiffen the soil fabric, thereby allowing fissuring and air entry at larger moisture contents as noted by Newman

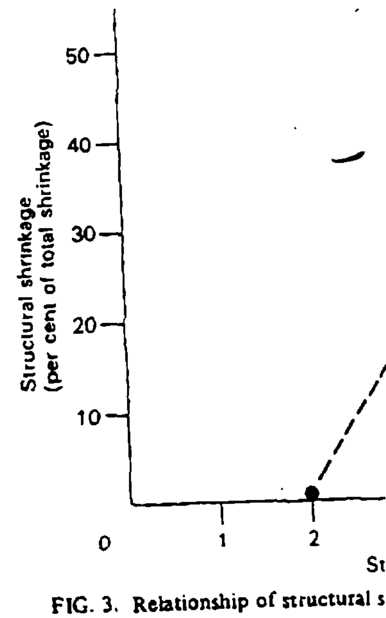

FIG. 3. Relationship of structural s

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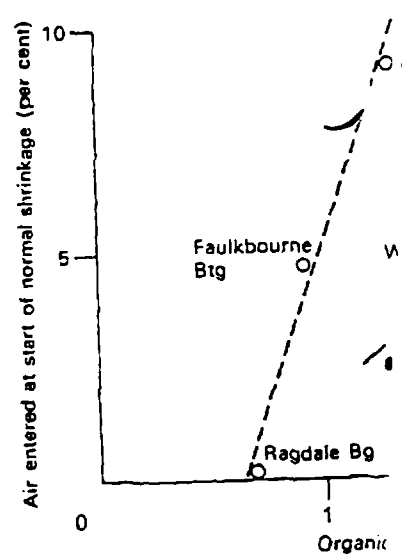
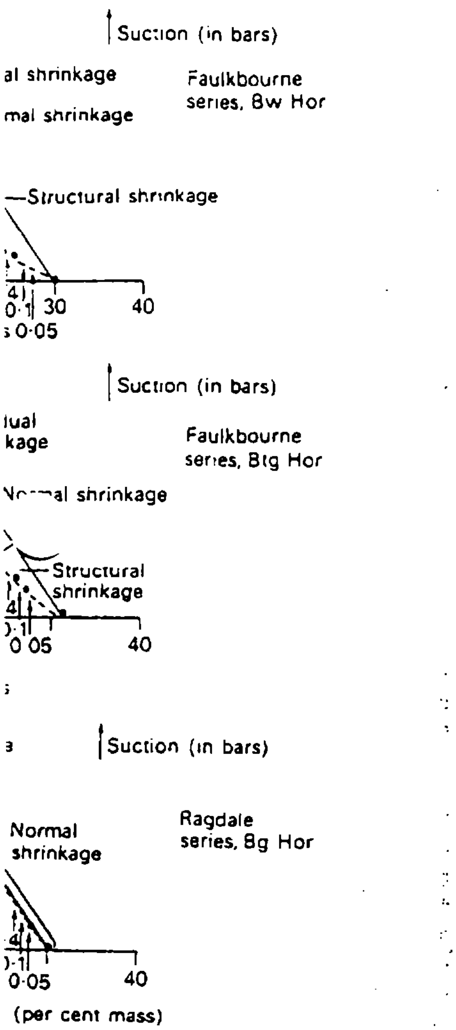


FIG. 4. Relationship of air



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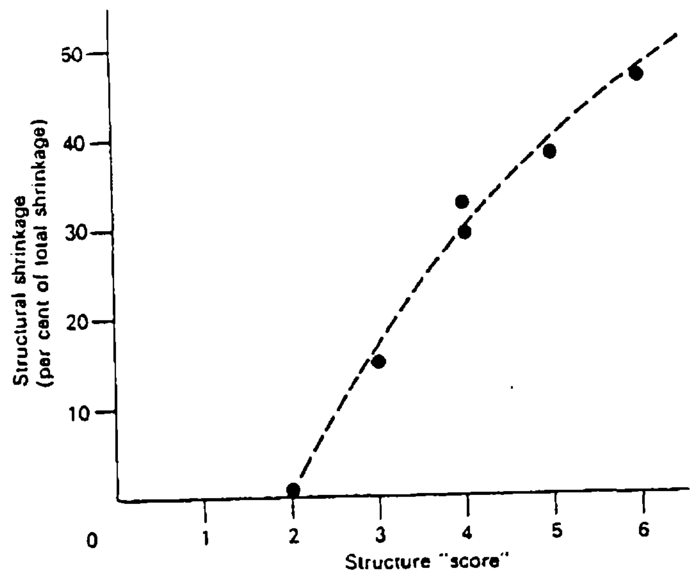

FIG. 3. Relationship of structural shrinkage to soil macrostructure.

and Perrins (1977) when working with small aggregates. However, the Faulkbourne and Ragdale soils appear to lie on a different line to that of the Fladbury and Wyre samples, indicating that clay content, mineralogy or initial density cannot be ignored when considering the reasons for air entry.

When soil cracks in the field, structural shrinkage must affect plant growth and cultivations. Except in very dry summers, subsoils in Britain seldom lose water

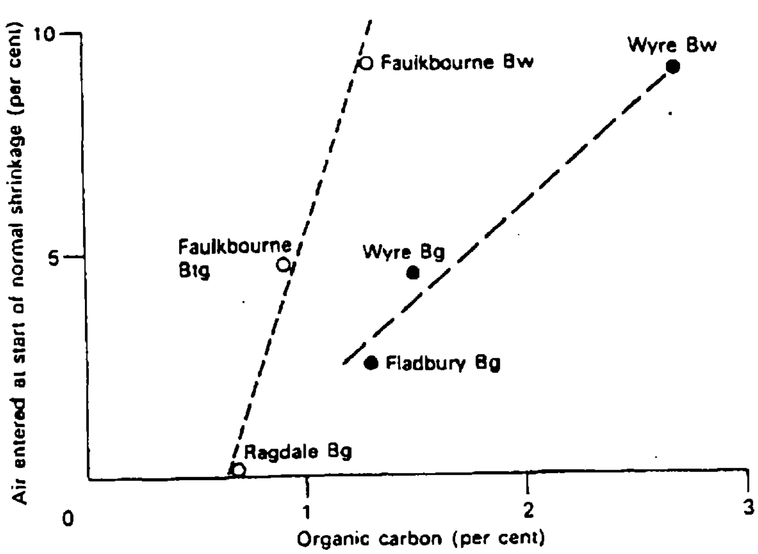

FIG. 4. Relationship of air entry to organic carbon content.

beyond 15 bar suction and often little above 2 bar suction. If shrinkage was normal over the field range of suction, contraction of the soil would be almost entirely by the shrinkage of individual peds and the formation of inter-ped cracks, the spacing of which would be related to the size of structural aggregates, and the width partly to this spacing and partly to the degree of drying. Contraction of a ped would reduce internal pore sizes, hinder root penetration, and rapidly increase ped density needing more power for subsoil cultivations. However, a soil with good structure and hence significant structural shrinkage would allow more air to enter during drying, maintaining a more favourable pore-size distribution, and would have a slower rate of density increase. After very dry summers such as 1976, the subsequent re-wetting in autumn could also be expected to proceed more efficiently in the better structured soils with a more evenly distributed air-filled porosity.

It is for these reasons among others that clay soils having good structural quality due to their parent material, position in the landscape, developmental history or water regime, are able to keep it under intensive cultivation while poorly structured soils deteriorate. Drying, in the former, is a reconditioning process, whereas in the latter it is mainly a cyclical process with negligible benefit.

Acknowledgements

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THE EFFECT OF SOIL COMPOSITION AND ENVIRONMENTAL FACTORS ON THE SHRINKAGE OF SOME CLAYEY BRITISH SOILS

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Summary

The shrinkage potential of natural clods from a variety of clayey soils was measured and related to their physical, chemical and mineralogical properties. It is shown that the most important factors affecting shrinkage are initial bulk density, clay content, organic carbon content and cation exchange capacity of the peroxidised clay, and mica-smectite content on a whole soil basis. Multiple regression equations involving the initial bulk density, clay content, organic carbon and cation exchange capacity accounted for 87 and 82 per cent of the variation in total shrinkage of topsoils and subsoils respectively.

Because of restrictions on shrinkage imposed by factors such as climate, crops, ground-water and moisture release characteristics of soils, soils with a high shrinkage potential may not behave very differently to soils with a much lower potential. On these grounds it is concluded that the shrinkage criteria used in US Taxonomy are not applicable in Britain.

Introduction

SUMMER cracking resulting from shrinkage on drying occurs to some extent in most soils but it is most recognisable in the field in fine textured soils. The magnitude of cracking varies according to soil type and soil moisture deficit, but in extreme years can involve surface cracks 5 cm across and 1 m deep.

The formation of shrinkage cracks is important not only for structural development (White, 1966) and regeneration (Reeve and Hall, 1978) but also aids infiltration of water in summer when the cracks are open and in winter as long as the cracks remain open (Blake *et al.*, 1973; Ritchie and Adams, 1974). Soils with large shrink-swell potential are of particular importance to civil engineers because of the problems they can cause to engineering structures.

In the USDA system of soil classification, soils that crack are placed in the Vertisol order or in vertic subgroups of other orders according to whether shrink-swell is the dominant or subordinate process (Soil Survey Staff, 1975). Although in a temperate climate soil shrinkage is unlikely to occur to the magnitude and frequency required for Vertisols (resulting in features such as gilgai), many soils have a high shrinkage potential. The classification introduced for use by the Soil Survey of England and Wales (Avery, 1973) proposed shrinkage and cracking criteria for separating a 'pelosol' group and

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'pelo' subgroups, but the criteria are less restrictive in terms of cracking, thickness of the clay layer and potential linear extensibility (Soil Survey Staff, 1975) than those for Vertisols and vertic subgroups.

The present study was undertaken because of the lack of information about the shrinkage potential of field soils in Britain. It has a threefold aim (i) to compare the shrinkage potential of different clayey soil series using natural soil clods; (ii) to determine the relationships between shrinkage and selected physical, chemical and mineralogical properties of the soils; and (iii) to determine whether criteria used in the Avery (1973) classification can be improved and to investigate the extent to which shrinkage criteria in the U.S.D.A. Soil Taxonomy are applicable to British conditions.

The soils

Nineteen soil profiles from fourteen commonly occurring clayey soil series were sampled (Table 1). Most were from pits dug to characterise soil series as part of the current or recently completed soil mapping; several were from the Long Buckby area in Northamptonshire (Reeve, 1978). Within these limits the soils were chosen to provide a range of clay mineralogy. The preponderance of smectite, micaceous and mixed mineralogy classes conforms with what is known nationally about the mineralogy of clayey soils (Avery and Bullock, 1977).

Sampling and analytical methods

Most samples were taken during the early spring when the soils were at or very near field capacity. Early winter sampling was avoided because clayey soils may take two or three months to swell fully after a return to field capacity (Smith, 1973).

A selection of clods was taken from each main horizon of the profiles. Bulk samples for Atterberg limits, particle size and clay mineralogical analyses, and cylindrical cores for moisture release measurements were also taken.

Replicated clods of 100–200 g (50–120 cm³) from each horizon were prepared by random division of the larger field clods. These were re-wetted within a few days on saturated foam to restore any small amount of moisture lost during transport to the laboratory and then placed on a 0.05 bar tension table for two or three hours to drain the coarsest pores (>60 μm e.s.d.). They were then suspended in a cradle of thread and coated with a 1:5 (w/w) solution of 'Saran' resin and butanone according to the method of Brasher *et al.* (1966). The Saran coating allows the passage of water vapour during drying and maintains close contact with the clod during shrinkage but acts as a barrier to liquid water when the volume of the clod is determined by displacement of water. After coating, the clods were suspended and allowed to dry. Measurements of mass and volume were made periodically, usually daily over the moist end of the shrinkage curve, decreasing to weekly as the clods dried. When the volume lost between weighings became negligible, the clods were oven-dried at 105°C and re-weighed.

For comparison with shrinkage criteria used in the United States, the indices 'coefficient of linear extensibility' (COLE) (Grossman *et al.*, 1968) and 'potential linear extensibility' (PLE) were calculated. The former can be

TABLE 1
Location, parent material and classification of the soils

Grid reference	County	Soil series	Geological system	Geological series/ formation/division	Classification	Clay mineral class
SO789241	Gloucestershire	Worcester	Triassic	Mercian mudstone	Typical argillic pelosol	Micaceous*
SP301556	Warwickshire	Worcester	Triassic	Mercian mudstone	Typical argillic pelosol	Micaceous
SP299557	Warwickshire	Spetchley	Triassic	Mercian mudstone	Pelo-stagnogley soil	Micaceous* over smectitic
SS678159	Devon	Tedburn	Carboniferous	Welcombe formation	Pelo-stagnogley soil	Micaceous
SS643151	Devon	Halstow	Carboniferous	Welcombe formation	Typical non-calcareous pelosol	Micaceous
SP647630	Northamptonshire	Long Load	Jurassic	Upper Lias Clay	Pelo-stagnogley soil	Mixed
TF037000	Cambridgeshire	Denchworth	Jurassic	Great Oolite Clay	Pelo-stagnogley soil	Smectitic
TL045992	Cambridgeshire	Denchworth	Jurassic	Upper Estuarine Series	Pelo-stagnogley soil	Smectitic over mixed
SP646622	Northamptonshire	Hornton	Jurassic	Upper Lias Clay	Typical argillic pelosol	Smectitic over mixed
SP647628	Northamptonshire	Hornton	[illegible]ssic	Upper Lias Clay	Typical argillic pelosol	[illegible]
[illegible]	Northamptonshire	Ragdale	Pleistocene	Chalky Boulder Clay	Pelo-stagnogley soil	Smecti[illegible]

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TABLE I
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SO789241	Gloucestershire	Worcester	Triassic	Mercian mudstone	Typical argillic pelosol	Micaceous*
SP301556	Warwickshire	Worcester	Triassic	Mercian mudstone	Typical argillic pelosol	Micaceous
SP299557	Warwickshire	Spetchley	Triassic	Mercian mudstone	Pelo-stagnogley soil	Micaceous* over smectitic
SS678159	Devon	Tedburn	Carboniferous	Welcombe formation	Pelo-stagnogley soil	Micaceous
SS643151	Devon	Halstow	Carboniferous	Welcombe formation	Typical non-calcareous pelosol	Micaceous
SP647630	Northamptonshire	Long Load	Jurassic	Upper Lias Clay	Pelo-stagnogley soil	Mixed
TF037000	Cambridgeshire	Denchworth	Jurassic	Great Oolite Clay	Pelo-stagnogley soil	Smectitic
TL045992	Cambridgeshire	Denchworth	Jurassic	Upper Estuarine Series	Pelo-stagnogley soil	Smectitic over mixed
SP646622	Northamptonshire	Hornton	Jurassic	Upper Lias Clay	Typical argillic pelosol	Smectitic over mixed
SP647628	Northamptonshire	Hornton	Jurassic	Upper Lias Clay	Typical argillic pelosol	Vermiculitic over mixed
SP682629	Northamptonshire	Ragdale	Pleistocene	Chalky Boulder Clay	Pelo-stagnogley soil	Smectitic over mixed
SP665654	Northamptonshire	Faulkbourne	Pleistocene	Chalky Boulder Clay	Typical argillic pelosol	Smectitic over mixed
SE760391	Humberside	Foggathorpe	Pleistocene	Glaciolacustrine Clay	Pelo-alluvial gley soil	Smectitic over mixed over micaceous
SP632620	Northamptonshire	Fladbury	Recent	River Alluvium (Jurassic derived)	Pelo-alluvial gley soil	Smectitic
SO759225	Gloucestershire	Fladbury	Recent	River Alluvium (Triassic derived)	Pelo-alluvial gley soil	Smectitic
SP630619	Northamptonshire	Wyre	Recent	River Alluvium (Jurassic derived)	Gleyic brown alluvial soil	Smectitic
SO782218	Gloucestershire	Compton	Recent	River Alluvium (Triassic derived)	Pelo-alluvial gley soil	Smectitic
ST556817	Avon	Wentloog	Recent	Estuarine Alluvium	Pelo-alluvial gley soil	Smectitic
ST434712	Avon	Wentloog	Recent	Estuarine Alluvium	Pelo-alluvial gley soil	Smectitic over micaceous

*Much sepiolite

calculated from the equation

$$COLE = (V_{0.33}/V_d)^{1/3} - 1$$

where $V_{0.33}$ is the volume of clod at $\frac{1}{3}$ bar tension (in this case interpolated from graphs between the volumes at 0.1 and 0.4 bar) and V_d is the volume of the clod when air dry. The COLE values obtained in this study may be slightly larger than those obtained from clods coated when air dry (Grossman *et al*., 1968) as there is evidence (Tunny, 1970) that the Saran coating can restrict swelling of dry clods.

Whereas COLE is an index of horizon shrinkage, PLE represents the integration of COLE values for the upper 1m of the profile:

$$PLE(cm) = (COLE_1)(H_1) + (COLE_2)(H_2) + (COLE_3)(H_3) \ldots$$

where $COLE_n$ are COLE values for successive horizons from the surface to 1 m depth and H_n are the thicknesses of those horizons in centimetres.

Triplicate 222 cm^3 cores for moisture retention measurements were equilibrated on 0.05, 0.10 and 0.40 bar sand tension tables and at 15 bar on a pressure membrane apparatus (Hall *et al*., 1977). Curves relating water loss to volume change were drawn, and 0.05 and 15 bar water retention values related to them. Replicate clods generally gave parallel and nearly co-incident shrinkage curves (Fig. 1) which were averaged for the results shown in Table 2 and for the correlations.

Atterberg limits were determined by the methods in BS1377 (BSI, 1975) on moist untreated soil, any small stones or roots being removed by hand during preparation of the sample.

Organic carbon was determined by Tinsley's (1950) wet digestion method

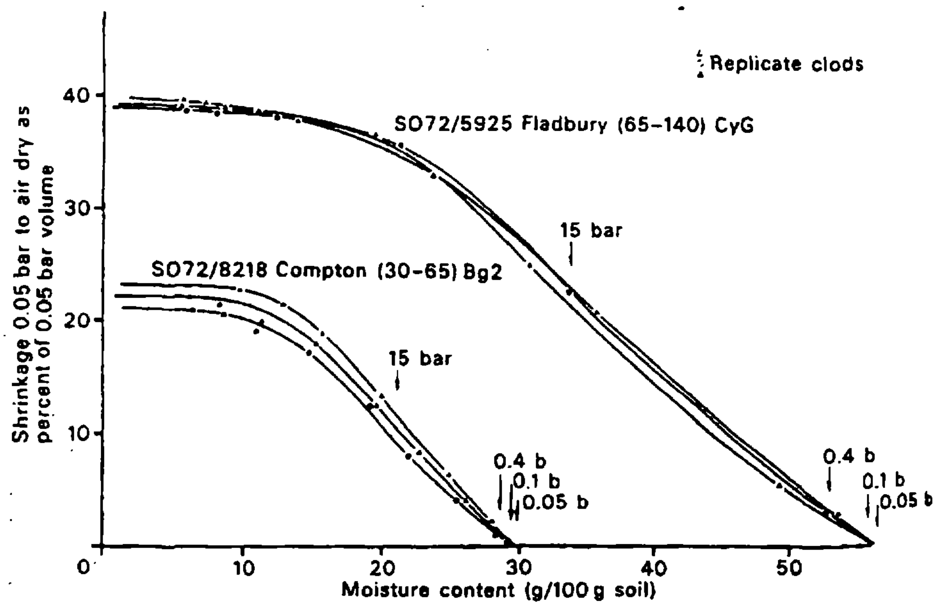

FIG. 1. Contrasting shrinkage curves for two subsoils.

TABLE 2

Shrinkage results for the ninet

Grid Reference and Soil Series	Horizon depth range (cm)	Volum... perce... 0.05 bar –air dry
SO789241 Worcester	0–25	21
	25–60	14
	25–60	16
SP301556 Worcester	0–25	21
	25–43	16
	43–69	14
SP299557 Spetchley	0–21	17
	21–48	20
	48–66	23
SS678159 Hedburn	0–20	19
	20–46	21
	46–94	18
SS643151 Halstow	0–20	14
	34–54	12
	54–78	11
SP647630 Long Load	0–25	26
	25–39	16
	(discontinuous) 25/39–85	27
TF037000 Denchworth	0–11	38
	11–42	42
	42–80	42
TL045992 Denchworth	0–13	29
	13–53	
	53–100	
SP646622 Hornton	0–25	27
	25–50	23
	50–100	13
SP647628 Hornton	0–27	32
	27–55	18
	55–120+	18
SP682629 Ragdale	0–21	19
	21–59	23
	59–120	21
SP665654 Faulkbourne	0–23	30
	23–47	18
	47–91/104	18
	91/104–120	14
SE760391 Foggathorpe	0–29	11
	29–43	15
	64–89	20

$\sqrt{V_d})^{1/3} - 1$

›ar tension (in this case interpolated
and 0.4 bar) and V_d is the volume of
lues obtained in this study may be
from clods coated when air dry
lence (Tunny, 1970) that the Saran

zon shrinkage, PLE represents the
er 1m of the profile:

$LE_2)(H_2) + (COLE_3)(H_3) \ldots$

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sand tension tables and at 15 bar on
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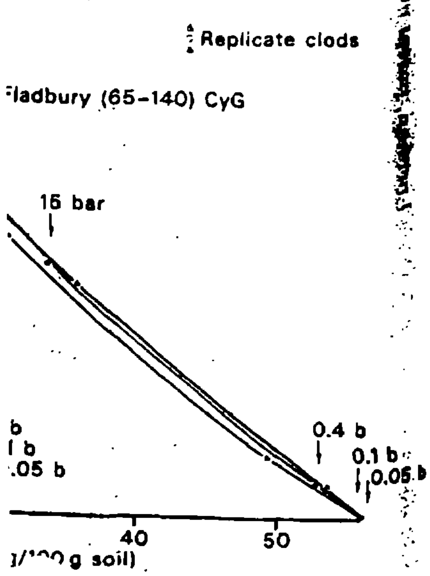

or two subsoils.

TABLE 2
Shrinkage results for the nineteen soil profiles

Grid Reference and Soil Series	*Horizon depth range (cm)*	*Volume reduction as a percentage of 0.05 bar volume* 0.05 bar –air dry	*Volume reduction as a percentage of 0.05 bar volume* 0.05 bar –15 bar	*COLE*	*PLE (cm)*
SO789241 Worcester	0–25	21	12	0.072	
	25–60	14	11	0.044	
	25–60	16	11	0.054	
SP301556 Worcester	0–25	21	13	0.073	
	25–43	16	9	0.053	5.2
	43–69	14	11	0.043	
SP299557 Spetchley	0–21	17	9	0.058	
	21–48	20	12	0.071	
	48–66	23	11	0.085	
SS678159 Tedburn	0–20	19	10	0.061	
	20–46	21	17	0.071	6.3
	46–94	18	10	0.060	
SS643151 Halstow	0–20	14	12	0.039	
	34–54	12	10	0.038	3.0
	54–78	11	9	0.031	
SP647630 Long Load	0–25	26	19	0.086	
	25–39	16	10	0.048	9.6
	(discontinuous) 25/39–85	27	19	0.100	
TF037000 Denchworth	0–11	38	21	0.140	
	11–42	42	15	0.194	18.5
	42–80	42	15	0.189	
TL045992 Denchworth	0–13	29	18	0.100	
	13–53	27	18	0.097	11.2
	53–100	32	13	0.129	
SP646622 Hornton	0–25	27	16	0.097	
	25–50	23	12	0.083	6.6
	50–100	13	7	0.042	
SP647628 Hornton	0–27	32	24	0.102	
	27–55	18	12	0.060	6.7
	55–120+	18	11	0.051	
SP682629 Ragdale	0–21	19	14	0.057	
	21–59	23	13	0.083	7.6
	59–120	21	12	0.080	
SP665654 Faulkbourne	0–23	30	17	0.111	
	23–47	18	11	0.062	7.4
	47–91/104	18	5	0.064	
	91/104–120	14	8	0.044	
SE760391 Foggathorpe	0–29	11	8	0.036	
	29–43	15	12	0.050	5.7
	64–89	20	15	0.069	

TABLE 2 continued

Grid Reference and Soil Series	Horizon depth range (cm)	Volume reduction as a percentage of 0.05 bar volume: 0.05 bar – air dry	Volume reduction as a percentage of 0.05 bar volume: 0.05 bar –15 bar	COLE	PLE (cm)
SP632620 Fladbury	0–20	47	18	0.219	15.5
	20–65	42	15	0.186	
	65–90	22	12	0.080	
SO759225 Fladbury	0–12	49	17	0.232	18.6
	12–30	44	16	0.203	
	30–65	40	14	0.181	
	65–140	39	22	0.168	
SP630619 Wyre	0–23	44	24	0.186	14.7
	23–45	33	15	0.132	
	45–70	33	9	0.137	
SO782218 Compton	0–10	44	21	0.203	11.5
	10–30	33	12	0.139	
	30–65	22	11	0.085	
	65–110	27	8	0.108	
ST556817 Wentloog	0–13	45	27	0.197	10.1
	13–40	25	16	0.087	
	40–85	24	16	0.087	
ST434712 Wentloog	0–17	33	21	0.119	10.8
	26–48	16	10	0.049	
	48–78	34	21	0.134	

and particle size distribution by the pipette method (Avery and Bascomb, 1974).

The non-exchangeable K_2O content of each clay separate was determined by digestion with HF and H_2SO_4 followed by flame photometry (Bullock and Loveland, 1974). The cation exchange capacity of clay separates was measured at pH 8.2 using an EDTA titration to determine the amount of magnesium exchanged from a standard solution by the barium-saturated sample (Bascomb, 1964).

The clay minerals in the separated >2 μm fractions were identified by X-ray diffraction and a semi-quantitative estimate was made of each by the techniques outlined in Avery and Bullock (1977). The CEC and K_2O determinations on the clay fraction were used in conjunction with the X-ray data to place the soil clays in classes (Avery and Bullock, 1977).

Shrinkage potential of the soils

PLE values are given for most profiles in Table 2 except where COLE determinations are unavailable for deeper subsoils. Where COLE determinations are available to almost 1 m, they are extrapolated to the full metre depth in order to calculate PLE. Volume reductions measured from shrinkage curves are given for two moisture ranges, 0.05 to 15 bar (representing the available water range) and 0.05 bar to air dry (total

shrinkage). The soils may be divid
shrinkage:
(i) Large shrinkage (PLE):
Denchworth soil in Great Oolite
(ii) Moderate shrinkage (PLE 9–1
Wentloog soils and a Denchwor
(iii) Low shrinkage (PLE < 9):
Tedburn, Foggathorpe, Horntor

For vertic subgroups of Haplaque
great groups relevant to the above
COLE of 0.09 or more in horizons
or more in the upper metre. The
shrinkage groups meet both these c
meet at least one of the criteria.

Shrinkage in relation to clay mineral

All horizons of the soils in the la
basis of the X-ray data and the cati
the expected relationship with s
shrinkage group includes soils which
at least one horizon classed as sme
have a variable clay mineralogy. Se
mineralogy (mainly mica and kaolin
a few have one or two horizons t
with smectitic horizons in the low
the known shrink-swell behaviour
explanations for this. One is that sl
calcium carbonate as Desphande *et*
(1976) have suggested. All but on
carbonate in the lower part
the fact that the smectitic zo
horizons, is that the CEC on which
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pre-treatment. In such cases, it is p
as smectitic when, in fact, some of t
the mineral components. Interstra
horizons in question but it is
determine the exact amount of it a
Correlations between total volu
percentage of the 0.05 bar volum
Table 3. They were also attempted
reduction over the available water
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Correlation between total soil shri
for interstratified mica-smectite, th
soils. The coefficients are 0.68 fo
values are considerably improved
expressed on a whole soil basis

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…reduction as a …e of 0.05 bar …olume			
…	0.05 bar –15 bar	COLE	PLE (cm)
	18	0.219	15.5
	15	0.186	
	12	0.080	
	17	0.232	18.6
	16	0.203	
	14	0.181	
	22	0.168	
	24	0.186	14.7
	15	0.132	
	9	0.137	
	21	0.203	11.5
	12	0.139	
	11	0.085	
	8	0.108	
	27	0.197	10.1
	16	0.087	
	16	0.087	
	21	0.119	10.8
	10	0.049	
	21	0.134	

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…ial of the soils

…les in Table 2 except where COLE… …deeper subsoils. Where COLE… …l m, they are extrapolated to the full… …ume reductions measured from… …sture ranges, 0.05 to 15 bar… …ge) and 0.05 bar to air dry (total…

shrinkage). The soils may be divided into three groups with respect to shrinkage:

(i) Large shrinkage (PLE > 14): the Fladbury and Wyre soils and a Denchworth soil in Great Oolite clay.
(ii) Moderate shrinkage (PLE 9–14): The Compton, Long Load and Wentloog soils and a Denchworth soil in Upper Estuarine series.
(iii) Low shrinkage (PLE < 9): The Worcester, Spetchley, Halstow, Tedburn, Foggathorpe, Hornton, Faulkbourne and Ragdale soils.

For vertic subgroups of Haplaquepts, Hapludalfs and Eutrochrepts (the great groups relevant to the above soils), the US Taxonomy requires a COLE of 0.09 or more in horizons at least 50 cm thick and a PLE of 6 cm or more in the upper metre. The soils of both the large and moderate shrinkage groups meet both these criteria but those in the low group fail to meet at least one of the criteria.

Shrinkage in relation to clay mineralogy

All horizons of the soils in the large shrinkage group are smectitic on the basis of the X-ray data and the cation exchange capacity, hence confirming the expected relationship with shrink-swell behaviour. The moderate shrinkage group includes soils which, apart from the Long Load series, have at least one horizon classed as smectitic. Soils in the low shrinkage group have a variable clay mineralogy. Several are micaceous, a few have a mixed mineralogy (mainly mica and kaolinite), one has a vermiculitic horizon and a few have one or two horizons that are smectitic. The inclusion of soils with smectitic horizons in the low shrinkage group is surprising in view of the known shrink-swell behaviour of smectite. There are two possible explanations for this. One is that shrinkage is depressed by the presence of calcium carbonate as Desphande *et al.* (1964) and Rimmer and Greenland (1976) have suggested. All but one of the profiles involved have calcium carbonate in the lower part of the profile. The other possibility, in view of the fact that the smectitic horizons are mostly surface or near surface horizons, is that the CEC on which assignment to the smectitic class is based is influenced by the presence of organic matter which resisted the peroxide pre-treatment. In such cases, it is possible that some horizons may be classed as smectitic when, in fact, some of the CEC is due to organic matter and not the mineral components. Interstratified mica-smectite was noted in all the horizons in question but it is not possible from X-ray diffraction to determine the exact amount of it and hence the CEC due to it.

Correlations between total volume reduction (0.05 bar to air dry as a percentage of the 0.05 bar volume) and various parameters are shown in Table 3. They were also attempted between the same variables and volume reduction over the available water range (0.05–15 bar) but generally gave low correlation coefficients, few significant at the 5 per cent level. Correlation between total soil shrinkage and individual clay minerals is best for interstratified mica-smectite, the form in which smectite occurs in all the soils. The coefficients are 0.68 for topsoils and 0.45 for subsoils but these values are considerably improved if the mica-smectite in the clay fraction is expressed on a whole soil basis (<2 mm). The respective values then

TABLE 3

Correlation coefficients (r) between total volume reduction and various parameters

	Parameter	Range	Correlation with volume reduction (0.05 bar-air dry) expressed as a percentage of volume at 0.05 bar: Topsoils (n = 19)	Subsoils (n = 42)
1	Bulk density at 0.05 bar (g cm^{-3})	0.68–1.74	−0.85**	−0.86**
2	Clay (<2 μm)	26–89	0.87**	0.64**
3	Fine clay (<0.2 μm)	4–59	0.71**	0.56**
4	Plastic limit (%)	19–72	0.72**	0.61**
5	Liquid limit (%)	38–144	0.87**	0.83**
6	Plasticity index (%)	19–78	0.88**	0.83**
7	Organic carbon (% C)	0.4–11	0.78**	0.56**
8	<2 μm K_2O (%)	1.11–5.49	−0.39	−0.14
9	<2 μm CEC (meq/100 g)	20.4–59.2	0.49*	0.63**
10	Kaolinite (parts in ten)	0–5	−0.08	−0.15
11	Illite (parts in ten)	1–8	−0.43	−0.19
12	Chlorite (parts in ten)	0–3	0.21	0.10
13	Vermiculite (parts in ten)	0–6	−0.38	−0.30
14	Mica-chlorite (parts in ten)	0–2	0.37	0.22
15	Mica-smectite (parts in ten)	0–6	0.68**	0.45**
16	Sepiolite (parts in ten)	0–3	−0.24	−0.20
17	Non-expansibles (10 + 11 + 12 + 14)	4–9	−0.43	−0.17
18	Non-expansibles (17 + 16)	4–9	−0.50*	−0.32*
19	Expansibles (13 + 15)	1–6	0.51*	0.30
20	CEC × $\frac{clay}{100}$	8.3–50.7	0.87**	0.80**
21	Mica-smectite × $\frac{clay}{100}$ (parts in ten)	0–4	0.87**	0.80**

Significance levels: *p = 0.05; **p = 0.01

become 0.87 and 0.80 and are among the best of the correlation coefficients (Table 3). Schafer and Singer (1976) also found a close relationship between amounts of expansible clay and COLE. However, their basing of a predictive model solely on interlayer expansion of smectite and swelling-interstratified minerals conflicts with the work of Greene-Kelly (1974). Although working with re-wetted air-dried sieved samples, he concluded that interlamellar shrinkage was unimportant at suctions below pF 4.6 (40 bar) and was several times smaller in magnitude than bulk shrinkage occurring through reduction in pore size.

Correlations between total shrinkage and other individual clay mineral species are low for kaolinite, mica, sepiolite and vermiculite whereas chlorite and mica-chlorite appear to contribute positively to shrinkage. Vermiculite is an expanding lattice mineral whereas chlorite (excluding swelling-chlorite) is a non-expanding mineral and these results give further weight to Greene-Kelly's findings. Correlation coefficients are low, however, and in a sample of this size only the correlation between shrinkage and mica-smectite is significant at either 5 per cent or 1 per cent levels. The groupings into

expansible and non-expansible clay min
are clearly in conflict with the above r
improvement in correlation.

Shrinkage in relation to physical and che

A variety of other factors, some ch
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swelling of a Houston Black Clay soil t
organic matter it contained.

Cation-exchange capacity is closely lin
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mineral classes. CEC of the clay fractio
with shrinkage but, as with mica-smecti
whole soil basis a very close positive c
Although total volume reduction is not
is measured from 0.05 and not 0.33 b
(about 5 per cent) of the total shrinkage
Hence the equation

$$V_r/100 = 1 - (C$$

(where V_r is the volume reduction b
percentage of the 1/3 bar volume),
approximate value of V_r corresponding
Fig. 2. This coincides with a subsoil CEC

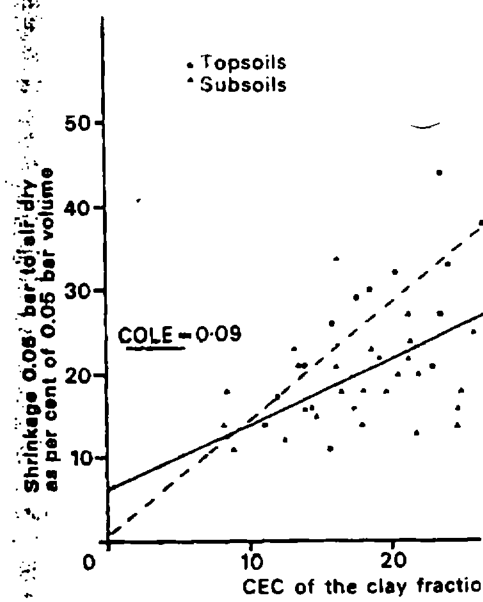

FIG. 2. Relationship between shrinka

E 3
›tal volume reduction and various
'ters

e	Correlation with volume reduction (0.05 bar-air dry) expressed as a percentage of volume at 0.05 bar Topsoils (n = 19)	Subsoils (n = 42)
.74	−0.85**	−0.86**
]	0.87**	0.64**
9	0.71**	0.56**
2	0.72**	0.61**
44	0.87**	0.83**
8	0.88**	0.83**
1	0.78**	0.56**
.49	−0.39	−0.14
9.2	0.49*	0.63**
	−0.08	−0.15
	−0.43	−0.19
	0.21	0.10
	−0.38	−0.30
	0.37	0.22
	0.68**	0.45**
	−0.24	−0.20
	−0.43	−0.17
	−0.50*	−0.32*
	0.51*	0.30
).7	0.87**	0.80**
	0.87**	0.80**

ıe best of the correlation coefficients
) also found a close relationship
1 COLE. However, their basing of a
yer expansion of smectite and
ts with the work of Greene-Kelly
›tted air-dried sieved samples, he
was unimportant at suctions below
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se results give further weight to
:ff--ients are low, however, and in a
ən shrinkage and mica-smectite
per cent levels. The groupings into

expansible and non-expansible clay minerals (Table 3) decided in advance are clearly in conflict with the above results and hence give little or no improvement in correlation.

Shrinkage in relation to physical and chemical parameters

A variety of other factors, some chemical, some physical, affect the tendency of a soil to shrink or swell. Organic carbon is positively correlated with the shrinkage of these soils, a finding which is at variance with the views of Davidson and Page (1956) who attributed the lower than expected swelling of a Houston Black Clay soil to the relatively large percentage of organic matter it contained.

Cation-exchange capacity is closely linked to the types of clay minerals in the clay fraction and consequently is used to aid the assignment of clay mineral classes. CEC of the clay fraction is only moderately well correlated with shrinkage but, as with mica-smectite, if the values are expressed on a whole soil basis a very close positive correlation is seen (Fig. 2, Table 3). Although total volume reduction is not directly related to COLE because it is measured from 0.05 and not 0.33 bar, usually only a small percentage (about 5 per cent) of the total shrinkage occurs between these two suctions. Hence the equation

$$V_r/100 = 1 - (\mathrm{COLE} + 1)^{-3}$$

(where V_r is the volume reduction between 1/3 bar and air-dry as a percentage of the 1/3 bar volume), can be used to determine an approximate value of V_r corresponding to a COLE of 0.09 as shown in Fig. 2. This coincides with a subsoil CEC of about 24 meq/100 g on a whole

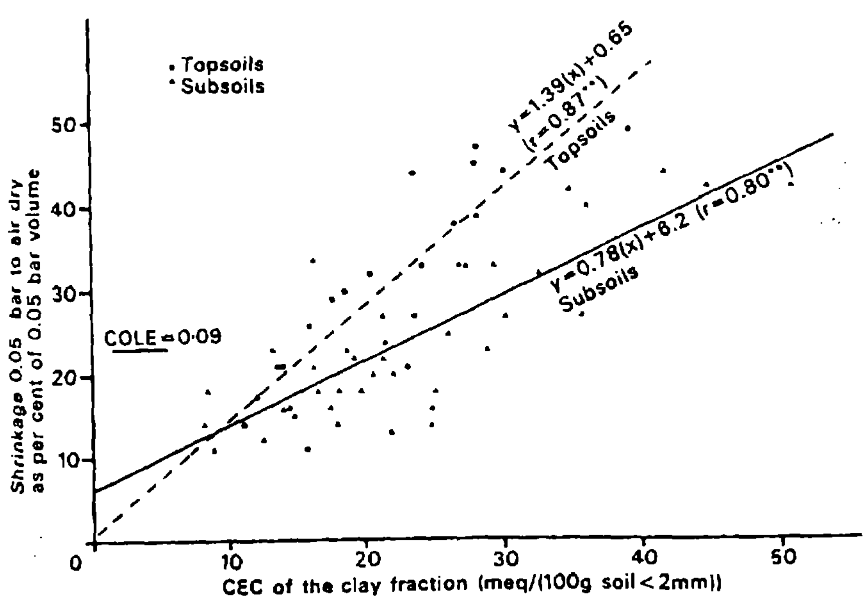

FIG. 2. Relationship between shrinkage and cation exchange capacity.

soil basis or 45 meq/100 g on a clay fraction basis for upper B horizons with an average of 54 per cent clay. Avery and Bullock (1977) separated smectitic clay mineral classes from others by a CEC (clay) of 45 meq/100 g: hence the use of clay mineral classes in soil series definitions (Reeve, 1978) will generally have physical (i.e. shrinkage) as well as chemical significance.

There is a close correlation between total clay and shrinkage but fine clay is apparently less important. McCormack and Wilding (1975) and Schafer and Singer (1976) draw similar conclusions from their study of the swelling behaviour of Ohio and Californian soils.

Liquid limit and plasticity index are much more closely correlated with shrinkage than is plastic limit.

The only factor which gives a similar and very close correlation in both topsoil and subsoils is the bulk density at 0.05 bar (Fig. 3). It is likely that the property of certain expansible minerals (such as interstratified mica-smectite) most responsible for shrinkage is their ability to form more open structures (and hence lower bulk densities) at low suctions as suggested by Greene-Kelly (1974). Certainly mica-smectite (whole soil basis) and dry bulk density at 0.05 bar suction are closely correlated ($r = -0.69$ topsoils, $r = -0.60$ subsoils) in this study. Bulk density is a property easily measured on cores or by gamma probe methods and, therefore, provided that the soil can be sampled in a moisture condition near to field capacity, an assessment of shrinkage potential can be made simply from a density measurement.

For a more accurate estimation of shrinkage potential a multiple regression analysis was made using the most important variables in Table 3 (viz. bulk density, clay, liquid limit, <2 mm CEC and organic carbon).

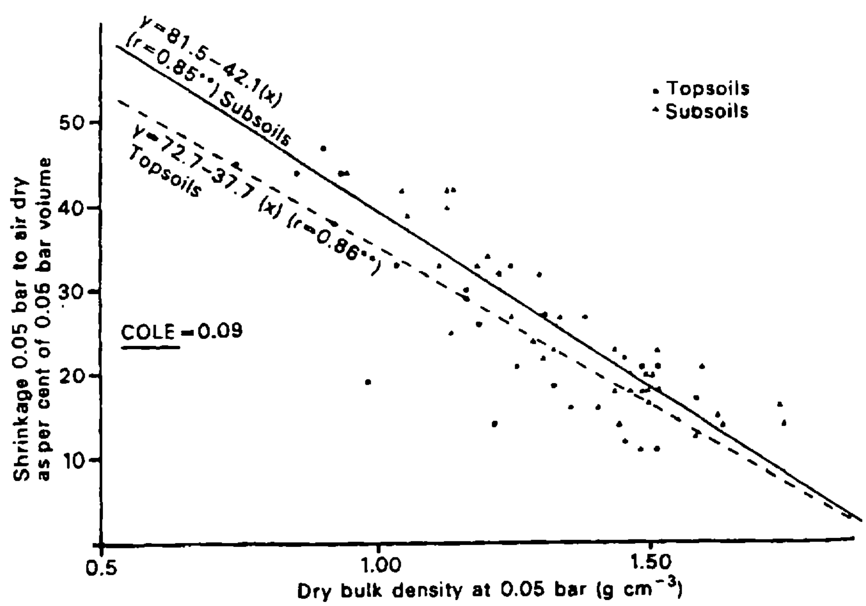

FIG. 3. Relationship between shrinkage and initial bulk density.

TABLE 4

Multiple regression equations for the de

Horizon	Regre
Topsoils	Volume reduction (0.05 bar to air d (Db) + 1.12** (CEC) − 2.1 (OC)
Subsoils	Volume reduction (0.05 bar to air d (Db) + 0.62** (CEC) − 0.19* (C

Db = dry bulk density at 0.05 bar (g cm⁻³)
CEC = cation exchange capacity of the clay fraction
OC = organic carbon (g/100 g soil)
C = clay (g/100 g soil)
Significance levels: *p = 0.05; **p = 0.01
Expressed as a percentage of volume at 0.05 bar

Several analyses were made, the best of regressions do not necessarily include all variation in shrinkage is accounted for b organic carbon in topsoils; and 82 per c and clay content in subsoils (Table 4). Mi basis was included in addition to other fac improve on the values quoted above.

The unexplained variation is proba experimental error and effects of factor experiment. Among the latter the effe aluminium oxides (Davidson and Page 1975) or the nature of the exchangeab 1968) are likely to be of low significance in restricting swelling may be significant

Field expression of shrinkage

In relating laboratory-measured shrink shrinkage, there are several factors to be for shrinkage can only be realised if environmental factors affecting soil wate Climate is one factor. The average m ranges from a negligible value in Snowd of Eastern England. Year to year va maxima as high as 400 mm. On a field limit the actual soil moisture deficit an influence the probability of the soil r vining peas which has a short growing s unlikely to cause shrinkage to the sam crop.

The pattern of cracking is also a fun within the soil. As noticed by Johnsto such as wheat and maize have concer the row which as they deplete soil n contract towards the row and cracks to develop in between the rows. Other crops with profuse fibrous root systems initiate a more regular dendritic pattern of surface cracks.

Local soil drainage is also important; a groundwater-table at shallow depth during part of the growing season will maintain the soil in a moist condition and lessen the potential for shrinkage.

Nevertheless, in a dry season, certain soils under certain crops will shrink markedly and the shrinkage will be expressed as cracking and lowering of the soil surface.

The distinctiveness of cracking at the soil surface will be affected by the size of soil structural units. It has been noticed that surface cracking in a long-established grass crop is less obvious than in a recently sown ley or arable crop. The finer structure formed under old grass presumably allows linear shrinkage to take place by means of a large number of fine cracks, but the coarser structure prevailing in frequently tilled clayey soils results in larger, more widely spaced cracks.

Where crack spacing and width are easily measurable and if it is assumed that shrinkage of structural units is isotropic, field-recorded surface crack widths compare well with potential crack widths calculated from laboratory shrinkage data. Thus a calculated potential crack width of 5 cm for surface cracks 25 cm apart (a common spacing) in a Fladbury series topsoil accords well with measured 5 cm cracks during the summer of 1975. This confirms that shrinkage was isotropic.

Below the surface, cracks normally narrow with increasing depth corresponding to a reduction of soil moisture tension. Evidence from pits dug during dry summers in England and Wales shows that cracks more than 1 cm wide often extend to between 50 and 60 cm depth but narrow rapidly below that, although often extending as fine cracks to depths of more than one metre. In the subsoil, water loss in response to direct evaporation is insignificant (Ritchie and Adams, 1974) and only occurs along crack walls. Hence transpiration by the growing crop accounts for the majority of drying. As most crops are unable to extract water beyond 15 bar tension, only shrinkage to that point is relevant.

Table 2 shows that subsoil shrinkage within the available water range varies from 5 to 22 per cent in the soils studied. At the higher end of the range, a potential crack width of 1.5 cm is suggested if the spacing is 25 cm. The observed crack widths in subsoils are well within this potential and indicate that drying to 15 bar seldom occurs in such soils below 60 cm depth.

Because drying beyond 15 bar is rare in subsoils in Britain the potential shrinkage differences between soils become less significant. This can be demonstrated by the following comparison of two different soils.

A total potential volume reduction of over 40 per cent in a Fladbury subsoil becomes a potential shrinkage of only 15 per cent within the available water range, as much of the total shrinkage would require loss of water held at very high tensions. The total potential shrinkage of a Worcester series subsoil at 15 per cent is less than half that of a Fladbury soil, but more than two thirds (10–11 per cent) is attributable to the available water range. Additionally, the lower available water capacity of Worcester soils (12 per

cent as opposed to 16 per cent in a Fladbur
are found in situations above any grou
Worcester soils will be more likely to dry
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For the above reasons, it becomes invidi
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(Heaven, 1978; Reeve, 1978) soils w
pelo-subgroups on the sole basis of cla
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Conclusion

Of the 19 profiles studied, nine meet bo
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There is a good correlation between
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Due to restriction on shrinkage impose
the ground-water depth and moisture r
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cent as opposed to 16 per cent in a Fladbury subsoil) and the fact that they are found in situations above any groundwater influence means that Worcester soils will be more likely to dry to higher tensions that Fladbury soils. Thus it is hardly surprising that in the field and under similar crops, soils of the Worcester series will exhibit as much shrinkage as Fladbury series over the shorter drought periods. This fact explains why Worcester subsoils are as likely to show slickensides (Avery and Bullock, 1977) as are soils of smectitic mineralogy.

For the above reasons, it becomes invidious to classify soils separately in Britain in terms of measurements of shrinkage between low tensions and an air-dry state, as many other factors are involved. The application of COLE and PLE criteria introduced by Avery (1973) has consequently been abandoned by the Soil Survey of England and Wales. In recent surveys (Heaven, 1978; Reeve, 1978) soils were classified into pelosols or pelo-subgroups on the sole basis of clay content and horizon thickness requirements.

Conclusions

Of the 19 profiles studied, nine meet both the COLE and PLE criteria for vertic horizons. Six of these are in riverine alluvium, the others in Jurassic clay.

There is a good correlation between interstratified mica-smectite and shrinkage particularly when the amounts of mica-smectite are given on a whole soil basis. Correlation with six other minerals in the clay fraction (mica, kaolinite, chlorite, vermiculite, mica-chlorite and sepiolite) is not significant at either 5 per cent or 1 per cent levels.

Of the other factors affecting shrinkage that were studied, bulk density, liquid limit, clay content, organic carbon content and CEC on a whole soil basis all gave good correlations. Regression equations involving these parameters explain 87 per cent and 82 per cent of the shrinkage in topsoils and subsoils respectively. It is therefore, possible to estimate shrinkage potential fairly accurately in most temperate clayey soils using these parameters.

Due to restriction on shrinkage imposed by such factors as climate, crops, the ground-water depth and moisture release characteristics, soils with a large potential shrinkage may not behave very differently from soils with a much lower COLE. For these reasons the United States COLE and PLE criteria have been excluded from the classification system for England and Wales.

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Woody Plant Roots Fail to Penetrate a Clay-Lined Landfill: Management Implications

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ABSTRACT / In many locations, regulatory agencies do not permit tree planting above landfills that are sealed with a capping clay, because roots might penetrate the clay barrier and expose landfill contents to leaching. We find, however, no empirical or theoretical basis for this restriction, and instead hypothesize that plant roots of any kind are incapable of penetrating the dense clays used to seal landfills. As a test, we excavated 30 trees and shrubs, of 12 species, growing over a clay-lined municipal sanitary landfill on Staten Island, New York. The landfill had been closed for seven years, and featured a very shallow (10 to 30-cm) soil layer over a 45-cm layer of compacted grey marl (Woodbury series) clay. The test plants had invaded naturally from nearby forests. All plants examined—including trees as tall as 6 m—had extremely shallow root plates, with deformed tap roots that grew entirely above and parallel to the clay layer. Only occasional stubby feeder roots were found in the top 1 cm of clay, and in clay cracks at depths to 6 cm, indicating that the primary impediment to root growth was physical, although both clay and the overlying soil were highly acidic. These results, if confirmed by experimental research should lead to increased options for the end use of many closed sanitary landfills.

Restrictions on Use of Woody Plants on Closed Landfills

Modern landfill technology includes methods for isolating landfill contents, largely to prevent wetting of the contents and subsequent pulses of leachate that might contaminate surrounding lands and waters. This is accomplished by sealing the top of a completed landfill with an impermeable liner, using one of two methods. Either a thick layer of dense clay is spread over the top and sides of the mounded trash, or the mound is carpeted with a synthetic waterproof fabric (a goetextile). Both types of linear are covered with a layer of soil, which is designed to function as a combination barrier protection layer, drainage channel, and growth medium. Both systems are engineered to function for several decades, during which time landfill contents are expected to slowly decompose anaerobically (Anonymous 1980, Lutton 1982, Oweis 1989, Miller 1988, Woodward 1989).

Given their constant shifting and settling, closed landfills are often unsuitable for building construction, and options are limited to their end use (e.g., Aplet and Conn 1977). Therefore, the main defining feature of many closed landfills, other than shape and size, will be their vegetative cover. Although the soil materials used for final cover, including surface layers, are designed primarily for containment, most sites can accommodate a variety of plant communities, if provided sufficient soil cover (Carnell and Insley 1982, Bradshaw 1984). Typically, however, the vegetation is engineered to match the site, rather than the reverse. Part of the reason for this approach lies with fears that some types of vegetation might interfere with containment. In cases where final cover includes synthetic geotextiles, that concern has been somewhat alleviated by tests demonstrating that those materials are resistant to penetration by tree roots (Landreth 1991, Dobson and Moffat 1993). However, on clay caps, landscaping materials are often restricted by law to herbaceous plants (e.g., grasses and wildflower mixes), out of concern for potential damage to clay barriers posed by woody plant roots.

The origin of those concerns is not clear, although they are expressed in regulations and technical guidelines (e.g., Anonymous 1989, 1991, 1992, citations in Dobson and Moffat 1993). It is not even clear that herbaceous plants should be any less threatening than trees and shrubs. For example, roots of native bunch grasses from the Great Basin of western North America are known to reach depths of several meters (Weaver 1920) in their native soils. Indeed, studies of clay-capped landfills in Wisconsin, USA, indicate that

KEY WORDS. Clay liner, Environmental regulation; Restoration ecology; Root penetration; Sanitary landfills; Woody plants

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Figure 1. Field level photograph of a portion of the Brookfield Landfill, taken in June 1993. The large trees in the foreground are black locust, *Robinia pseudoacacia*.

stringent standards, and we were granted permission by the New York City Department of Sanitation to excavate the woody plants on the site.

In fall 1992, we excavated 30 trees and shrubs, of 13 species, that had been growing for up to seven years. For the most part, they represented the largest specimens available, but some species were represented by a single individual. Species with small, short-lived stems (e.g., blackberries, *Rubus* spp.) were excluded. For each plant sampled, we chopped through the main lateral roots in a circle of 1–2.5 m diameter (depending on plant size), removed surface soil from around the attached roots, dug out the exposed root mat, and tipped the plant on its side. Within the area excavated, any remaining soil was scraped to expose the clay cap, which was examined for the presence of plant roots, living or dead. Maximum root depth of the excavated plant was measured, as well as the overburden soil depth, and the maximum diameter of the largest exposed root. Each plant was aged by counting growth rings, and each plant's size was determined by measuring basal stem diameter and height from soil surface to the tallest growing bud. To estimate potential physical resistance to root growth in both soil and clay, probes were made with a spring-type penetrometer (Soil Test Incorporated Pocket Penetrometer), which provides a relative measure of resistance to a calibrated force (McKyes 1989, Bengough 1991, Campbell and O'Sullivan 1991). All probes were made in the field following a rain, in order to obtain moist soil conditions. Beneath each plant, 250-cc samples of soil overlaying the clay cap were removed for laboratory pH tests, using a laboratory electrode inserted in a slurry of homogenized soil and distilled water (McLean 1982).

Results

Nineteen species of woody plants were found growing on the landfill; 13 had sizable individuals living above the clay cap. Judging from their ages, many of the sampled trees and shrubs had begun growing on the site soon after the cap was installed. All 30 plants examined, including the largest, had extremely shallow root plates (Figure 2). Tap roots of all sizes were deformed in many cases (Fig. 2C,D), growing entirely above and parallel to the clay layer. A few small feeder roots were found in the top 1 cm of clay, and in several cases, in cracks at depths of up to 6 cm, but no significant penetration of the clay cap was observed. Maximum root depth was typically equivalent to the depth of the soil overlying the clap cap (Table 1). Despite the very shallow soils, many of the plants were not particularly small for their ages and were apparently able to maintain sizable root volumes that spread well beyond the canopies.

Soil pH beneath each specimen was substantially higher than that of the underlying clay (4.0 vs 3.1, on average), although values for the soil were themselves quite low, perhaps due to acidification by the clay cap (R. Duell personal communication). Mean penetrometer resistance measurements were 0.54 MPa for the soil and 2.36 MPa for the clay. Values for the clay increased with depth, and measurements taken at depths >10 cm were off the scale of the instrument, >3.10 MPa. Values above 2.0 MPa indicate strong potential root impedance (Glinski and Lipiec 1990,

Table 1 Measurement data from 30 excavated trees and shrubs growing over a clay liner on Brookfield Landfill, Statin Island, New York[a]

Species	Common name	Height (cm)	Basal diam (cm)	Age (yr)	Soil depth (cm)	Root depth (cm)	Root diam. (cm)	Soil pH	Clay pH
Tree species									
Betula populifolia	grey birch	170	2.5	4	8	8	2.5	**3.41**	2.84
		505	15.0	6	10	10	7.0	**3.14**	2.52
		400	8.0	5	12	15	4.0	**3.41**	3.14
Liquidambar styraciflua	sweet gum	380	8.0	5	17	21	2.5	**3.60**	3.20
Morus sp.	mulberry	310	8.0	7	35	35	4.5	**5.13**	3.12
Prunus serotina	black cherry	175	4.0	6	19	15	3.5	**4.09**	3.47
		210	3.5	7	20	15	3.0	**4.01**	3.32
		440	22.0	7	12	13	13.0	**3.97**	3.16
		393	12.0	7	20	21	7.0	**3.70**	2.73
		235	4.5	7	14	14	4.0	**3.71**	2.91
Quercus palustris	pin oak	245	6.0	5	19	20	5.0	**3.53**	3.03
Robinia pseudoacacia	black locust	360	8.0	6	20	21	8.0	**3.84**	2.90
		410	10.0	5	14	14	6.0	**3.70**	3.00
		405	6.0	4	24	24	4.0	**4.72**	2.96
		627	12.0	7	20	20	7.5	**4.75**	2.76
		533	11.0	7	33	28	6.0	**4.10**	3.70
Shrub species									
Baccharis halimifolia	groundsel bush	130	2.0	5	21	21	1.5	**4.33**	3.64
Cephalanthus occidentalis	buttonbush	125	4.5	5	21	21	2.5	**3.72**	3.01
Myrica pensylvanica	bayberry	115	2.0	5	25	17	2.0	**4.32**	3.56
		135	2.5	6	25	18	2.0	**4.28**	3.46
		110	2.5	5	18	18	2.0	**4.90**	3.19
		141	2.0	3	21	22	1.5	**4.00**	3.08
		107	1.5	3	20	21	1.0	**4.97**	2.67
Rhus glabra	smooth sumac	136	2.0	7	19	17	1.0	**4.41**	3.11
		235	3.0	7	17	13	1.0	**4.32**	3.05
		240	3.5	7	15	10	1.5	**3.29**	2.89
		167	1.0	6	22	17	1.0	**3.72**	3.18
		145	1.0	5	34	15	1.0	**4.17**	3.15
Sambucus canadensis	elderberry	195	2.0	5	24	26	1.5	**3.86**	2.83
Viburnum dentatum	arrowwood	200	3.0	6	35	29	2.0	**3.73**	2.65
Means		266	5.8	5.7	20.5	18.6	3.6	**4.03**	3.08

[a]Soil depth represents only the amount of cover material above the clay at each sample location.

dicative. Studies of root growth in heavy soils indicate that the types of clay used to seal landfills, with their high bulk densities and small pore sizes, will be impervious to plant roots, including those of woody species (Russell 1977, Ch. 8, Klepper 1987, Bennie 1991, Materechera and others 1991). In order to grow, a root must push aside soil particles or else work through soil pores, cracks in rocks, or other discontinuities. Whereas an extending root tip has a diameter of 0.1–3 mm, soil pore diameters range from 0.002 to 0.2 mm, with even lower values for pure clay (Taylor 1971, Rendig and Taylor 1989). Dense soils, with their small average particle size—especially compacted clays—represent strong barriers to root penetration, because the small pores are rapidly clogged with fine particles that accumulate around the root tips (Dexter 1986, Greacen 1986, Atwell 1993). The forces necessary to penetrate such soils are beyond the capability of most plants studied. Root tips of any plant species extend by cell enlargement, driven by turgor (osmotic–hydraulic) pressure, and there are absolute limits to the amount of force that can be generated under these circumstances (Dexter 1987, Glinski and Lipiec 1990, Whalen and Feldman 1990, Atkinson and Mackie-Dawson 1991). Tree roots are notorious for breaking pavement and cracking rocks, but this activity is driven by gradual increases in girth of roots already in place, not penetration by young, growing root tips (Hermann 1977).

Further Research Needs

Although our field data seem clear and consistent, additional experimental information is needed for three reasons. First, the duration of growth was short,

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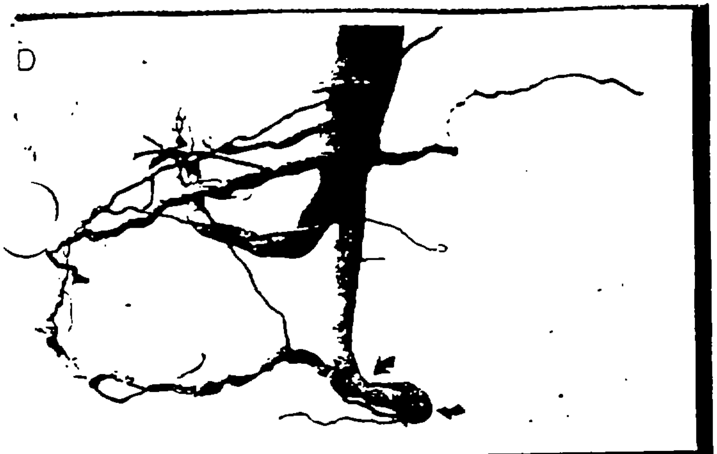

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Fig 2

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Fig 3a

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Fig 3b

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Survival, Reproduction, and Recruitment of Woody Plants After 14 Years on a Reforested Landfill

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ABSTRACT / With the advent of modern sanitary landfill closure techniques, the opportunity exists for transforming municipal landfills into urban woodlands. While costs of full-scale reforestation are generally prohibitive, a modest planting of clusters of trees and shrubs could initiate or accelerate population expansions and natural plant succession from open field to diverse forest. However, among woody species that have been screened for use on landfills, these ecological potentials have not yet been investigated. We examined a 14-yr-old landfill plantation in New Jersey, USA, established to test tolerance of 19 species of trees and shrubs to landfill environments. We measured survivorship, reproduction, and recruitment within and around the experimental installation. Half of the original 190 plants were present, although survival and growth rates varied widely among species. An additional 752 trees and shrubs had colonized the plantation and its perimeter, as well as 2955 stems of vines. However, the great majority (>95%) of woody plants that had colonized were not progeny of the planted cohort, but instead belonged to 18 invading species, mostly native, bird-dispersed, and associated with intermediate stages of secondary plant succession. Based on this evidence, we recommend that several ecological criteria be applied to choices of woody species for the restoration of municipal landfills and similar degraded sites, in order to maximize rapid and economical establishment of diverse, productive woodlands.

Of 6000 municipal landfills in the United States, about 20% have reached capacity, and many others will close before the year 2000 (O'Leary and others 1988). As with other kinds of landscape rehabilitation, efforts to revegetate former landfills have met with varying success, although in most cases the efforts themselves have been quite modest (Flower and others 1978). Until recently, former sanitary fills have been either covered directly with thin layers of mineral soil, or sealed first with an impermeable clay layer (to prevent leaching and to allow collection of decomposition gases), followed by lighter soils (US EPA 1980, Lutton 1982). For the most part, both types of site have been seeded with grass mixtures to control erosion, and, except in cases where building construction or other development was economical and otherwise feasible, subsequently abandoned (Flower and others 1978, US EPA 1980, Stalter 1984).

More elaborate landscaping programs have been hampered by considerations other than financial costs, since landfill closure methods have to a large extent limited the variety of plants suitable for site reclamation. In addition to stabilizing soils, landscapers have been required either to minimize groundwater contamination by leachate from unsealed landfills or to retain the integrity of sealed and vented sites. In response to the problem of leaching, the use of woody species has been proposed as a means of depleting excess soil moisture on uncapped landfills, provided soils are deep enough to support trees (Ettala 1987, 1988). However, on sites sealed with impermeable clay caps, woody plants have not been recommended, since their roots could penetrate the clay seal, releasing decomposition gases and allowing water to percolate downward. This latter problem does not apply to landfills sealed with synthetic polymer sheets (US EPA 1980b, Lutton 1982), which are impervious to root penetration (R. E. Landreth personal communication) and are now commonly used in place of clay to line and seal landfills. Consequently, uncapped sites and landfills covered with a polymer membrane barrier could be forested, given sufficient added soil, and opportunities exist to reclaim many of these degraded lands as urban forests and productive wildlife habitat. On both ecological and aesthetic grounds, woodlands may be a preferred end use in the environmental management of landfills.

An early step in any comprehensive restoration ecology program is characterizing the plant species most suitable to a particular site (Brown and others 1986, Malcom 1990). Where woody plants are appropriate, screening programs for sanitary landfills have typically focused on selecting plants that will survive in an ex-

KEY WORDS Restoration ecology; Plant succession, Seed dispersal, Plant reproduction, Landfills, Woody plants

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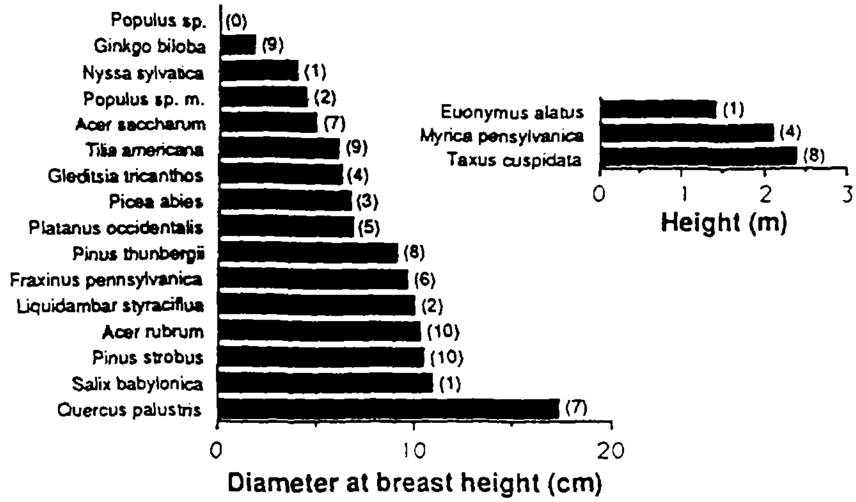

Figure 1. Average sizes (stem diameters) of surviving trees and average heights of surviving shrubs (inset), 14 yr after introduction on the Edgeboro landfill experimental plantation. Ten individuals were planted of each species. Values in parentheses are numbers of survivors per species.

in fall 1966. Upon closure, it was covered with a thin layer (15–25 cm) of mineral soil, seeded with a commercial grass mixture, and abandoned. Ten years later, in spring 1976, colleagues from Rutgers University chose a portion of the Edgeboro site to screen candidate species for landscaping municipal landfills. In an 800-m^2 plot, they added 60 cm of soil (including 30 cm of topsoil), planted ten individuals of each of 19 species of trees and shrubs, and studied their survival and growth over 4 yr. The saplings were nursery stock, ranging in approximate height from 1 to 3 m at planting (Gilman 1979, 1980, Leone and others 1979, Gilman and others 1985).

The central issue in their study was the effect of methane, carbon dioxide, and other decomposition gases on root development and aboveground growth of woody plants. The species chosen were horticultural varieties, selected on the basis of known tolerance to air pollution or waterlogging and other anaerobic soil conditions. The experimental plot was placed, by design, above a region where high levels of methane had been detected. Although additional experimental treatments were later conducted on this site (Leone and others 1979, Gilman 1980), we restricted our censuses to the original screening ensemble.

To estimate growth and survival, we first consulted the original planting diagram (Gilman 1979, p. 31) to ensure that we examined the transplants, not their offspring or other secondary recruits. For size estimates, we measured diameters at breast height (dbh) of trees and heights of shrubs. We judged a species to be reproductive if it bore flowers or fruit, was represented by seedlings, or had produced clonal shoots away from the parent stem.

For woody recruits in the plantation (defined for our purposes as the area bounded by the outside edge of the canopy), we divided the area into 3-m-wide strips and counted stems of all species in all strips. To examine recruitment around the plantation, we counted stems within a perimeter extending 5 m from its edge. We classified trees and shrubs by height, below or above 50 cm (to crudely differentiate seedlings from older plants). Vines (or more properly canes, in the case of *Rubus*) trailed along the ground or climbed stems of other species, and rather than classify by size, we counted emerging stems at ground level.

Results

Survivorship and Growth

All but one of the 19 species had at least one survivor, and nearly half of the original 190 plants were present. We had no means of determining causes of death, but losses during the 4-yr course of the original experiment—which amounted to 14%—were attributed to herbivory, desiccation, and possible soil toxicity (Gilman 1979, 1980). Survivorship was quite variable among species, as was average size, which ranged over an order of magnitude (Figure 1). Tree size was not correlated with the proportion surviving ($R^2 < 0.02$), an indication that survival probability and growth rate were influenced by different sets of factors.

Reproduction and Recruitment

Of the 18 planted species with at least one survivor, we found evidence for reproduction, from seeds or clonal growth, in nine (Table 1, A). Among them, the highest reproductive rates were for bayberry (*Myrica pensylvanica*), red maple (*Acer rubrum*), and pin o.

Table 2. Suggested ecological criteria for woody species selected to revegetate landfills and similar degraded or isolated landforms

Ecological component	Desired function	Species attributes
Survival and growth	Increase landscape complexity, compete successfully with weeds, improve soil properties	Tolerance to site environment, rapid growth rate, herbivore defences
Reproduction and regeneration	Retain species diversity, augment genetic diversity, increase vegetation coverage, provide future seed source	Early maturity, high pollination success, large allocation to reproduction, high recruitment success, long reproductive period
Disperser attraction	Ensure seed dispersal, promote desirable invasions, improve wildlife habitat	Perches and nesting sites, fleshy and attractive fruits, high fruit quality and quantity, sequential ripening for lengthy food resource
Transciency	Permit a natural successional mosaic	Relatively short-lived, typically early or mid-successional, invadable by additional desirable species

vines added nearly 3000 additional recruits, although their contribution to biomass was proportionately smaller. In the plantation's interior, 82% of recruiting trees and 84% of recruiting shrubs were from outside sources. Along the perimeter, the proportions were similar: 83% of trees and 73% of shrubs. Combining the original species and subsequent invaders, regeneration was primarily by native species, which represented 64% of all species, but 74% of all recruiting species, 92% of individual tree and shrub recruits, and 54% of individuals among recruiting vines. Among the species that had invaded, 16 of 18 had adaptations (principally berries) known to promote bird dispersal.

Over twice as many tree seedlings and saplings, of both the planted and invading populations, were found inside the plantation as on its margins. The opposite was true of shrubs, with three times as many individuals along the perimeter. Adjusting for differences in total area sampled (the amount of perimeter measured was ±80% of the experimental plot area), tree density was 45% higher and shrub density 395% lower within the plot than at its margins. Several species of vines were well represented in the recruiting vegetation, more so in the understory than the perimeter (Table 1, B). Recruit size appeared related to the light environment, with taller plants generally found along the margin or in more open areas within the plantation.

For planted species, recruits within the plot averaged only three stems per species, and on the perimeter only six per species, after 14 yr. Bayberry, a native shrub, had by far the highest reproduction (mostly in the form of clonally derived stems), contributing 71% of all recruits (Table 1, A).

Discussion

When end-use plans and financial resources are compatible with programs of natural restoration, sanitary landfills could be transformed into urban woodlands, greatly enhancing their aesthetic and educational values, increasing local biodiversity, and providing important wildlife habitat. Restored natural areas have already made a significant contribution to nature conservation in the United Kingdom (Bradshaw and Chadwick 1980, Wathern 1986, Buckley 1989). Costly restoration programs are not likely to be carried out on landfill sites, however, and we are investigating ecological means to restore natural plant diversity and succession in lieu of traditional landscaping and long-term site maintenance. It does seem likely that natural forces such as seed dispersal and reproduction can be utilized to accelerate a woodland vegetation, but the success of any such scheme would rest on a proper choice of species mixtures at the initiation of the process.

The definition of a successful landscaping specimen for landfill restoration has been restricted to its physiological capacity for survival and growth under potentially harsh conditions. To this we would add three criteria: (1) high and quickly realized reproductive capacity, (2) attractiveness to seed dispersers, and (3) relatively rapid turnover, to permit a continued successional sequence. The relevance of these criteria and the attributes that characterize them are outlined in Table 2.

Our reexamination of the Edgeboro landfill experimental plantation confirms a need for these added considerations. Clearly the capacity to survive and grow is

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Forest Restoration on a Closed Landfill: Rapid Addition of New Species by Bird Dispersal

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Abstract: *Urban areas often contain sizeable pockets of degraded land, such as inactive landfills, that could be reclaimed as wildlife habitat and as connecting links to enhance remnant natural areas. In the northeastern U.S., many such lands fail to undergo natural succession to woodland, instead retaining a weedy, herbaceous cover for many years. We hypothesize that seed dispersal is a limiting factor, and that a form of secondary succession could be stimulated by introducing clusters of trees and shrubs to attract avian seed dispersers. As a direct test, we censused a 1.5-ha experimental plantation on the Fresh Kills Landfill (Staten Island, New York) one year after installation, in search of evidence that the plantation was spreading or increasing in diversity. The 17 planted species, many from coastal scrub forests native to this region, were surviving well but contributed almost no seedlings to the area, in part because only 20% of the installed trees or shrubs were reproductive. Of the 1079 woody seedlings found, 95% came from sources outside the plantation; most (71%) were from fleshy-fruited, bird-dispersed plants from nearby woodland fringes. Although the restoration planting itself had not begun to produce seedlings, it did function as a site for attracting dispersers, who enriched the young community with 20 new species. One-fourth of all new recruits were from nine additional wind-dispersed species. Locations with a high ratio of trees to shrubs had proportionately more recruits, indicating that plant size contributed to disperser attraction. The density of new recruits of each species was dependent on distance from the nearest potential seed source. Introducing native species with the capacity to attract avian dispersers may be the key to success of many restoration programs.*

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Restablecimiento del bosque en una clausura: Rápida adición de especies por aves dispersoras

Resumen: *Areas urbanas usualmente contienen nucleos aislados de tamaño considerable, de tierras degradadas, como vertederos públicos inactivos que pueden ser reclamados como hábitat para vida silvestre, y como vínculos de conección para ampliar áreas naturales remanentes. En el Noreste de Estados Unidos muchas de estas tierras fracasan en el proceso natural de sucesión hacia bosques, en vez retienen por muchos años una cubierta herbácea de malezas. Nuestra hipótesis es que la dispersión de las semillas es un factor limitante. Una forma de sucesión secundaria puede ser simulada introduciendo conglomerados de árboles y arbustos, para atrear aves dispersoras de semillas. Como test directo nosotros sensamos 1.5-ha de una plantación experimental en el vertedero público de "Fresh Kills" (Staten Island, New York) un año después de la instalación, en la búsqueda de evidencia que demuestre que la plantación fue dispersada o incrementó en diversidad. Las 17 especies plantadas, muchas de arbustos costeros nativos de la región, sobrevivieron bien, pero, prácticamente, no contribuyeron en semillas en el área, en parte porque sólamente el 20% de los árboles o arbustos instalados fueron reproductivos. EL 95% de las 1079 plántulas leñosas encontrados provienen de fuentes fuera de la plantación; la mayoría (71%) provinieron de frutos de plantas dispersadas por pájaros de tierras de bosques aledáneas. Si bien la restauración de la plantación en sí misma no ha comenzado a producir plántulas, ha funcionado como sitio para atraer dispersores, que han enriquecido las comunidades jóvenes con 20 nuevas especies. Un cuarto de todos los nuevos reclutas provinieron de nueve species dispersadas por el viento. Lugares con altas relaciones de árboles con respecto a arbustos tuvieron proporcionalmente más reclutas, indicando que el tamaño de la planta contribuyó a la atracción del dispersor. La densidad de los nuevos reclutas de cada especie fue dependiente de la distancia desde la fuente potencial de semillas más cercana. La introducción de especies nativas con la capacidad de atraer aves dispersoras puede ser la clave del suceso de muchos programas de restauración.*

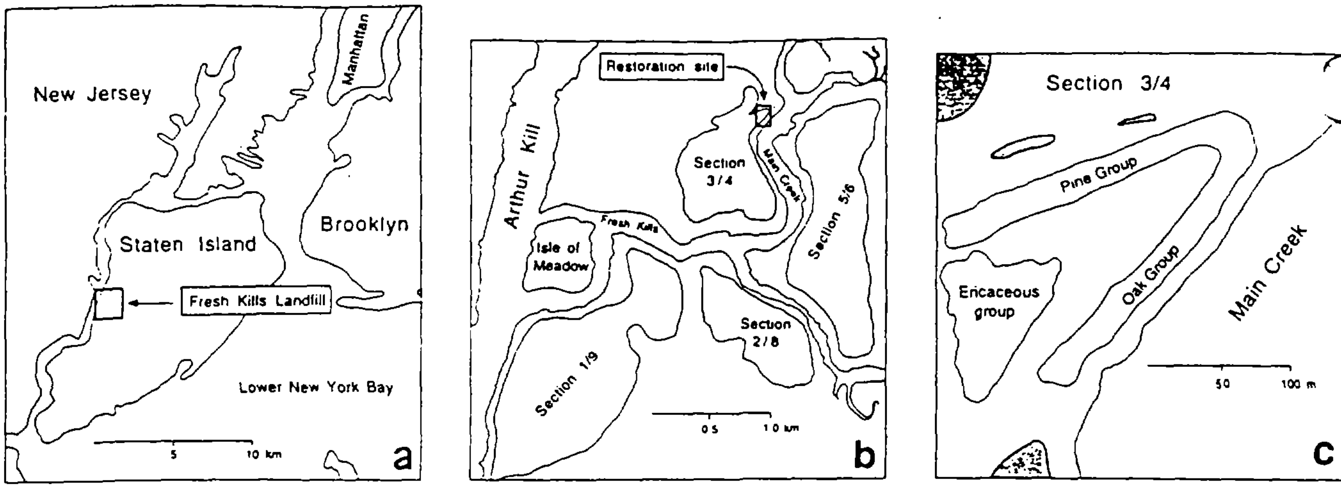

Figure 1. Maps of (a) Staten Island, New York, (b) the Fresh Kills Landfill complex, and (c) the coastal woodland restoration area examined in this study. The four numbered sections in (b) are the landfill mounds, parts of which have been capped with impermeable liners and revegetated. Shaded areas in (c) represent the approximate positions of nearby woodland remnants.

Three separate vegetation mixes were installed in three different portions of the site: (1) a predominantly oak-shrub mix of 14 species, planted on a south-facing slope approximately 25 m inland from Main Creek; (2) a predominantly pine-shrub mix of 14 species, planted on a shallow, north-facing upland swale 30 to 90 m inland from the oak-shrub group; (3) an ericaceous shrub mix of six species, planted upslope from the two other areas on a predominantly east-facing slope (Fig. 1). In the analyses that follow, these are referred to as the oak, pine, and ericaceous sites. Approximately 3000 shrubs were planted in small clusters (6–12 plants of one species per cluster) among the three sites, and 500 trees were distributed over the oak and pine sites. In addition to woody species, each site was planted with native perennial grasses and seeded with a native wildflower mixture.

We censused the plantation in June 1991, during the second growing season after installation. We divided the three sites into 50 contiguous plots, each approximately 10 × 30 m. To study survival and reproductive status of the planted stock, we censused all trees, shrubs, and woody vines within the three sites. To estimate recruitment, we censused all seedlings of woody plants, identified by species. Living individuals were counted, measured, and categorized according to one of four sources: (1) deliberately planted as part of the restoration; (2) a seedling derived from one of the restoration plants (as a conservative estimate, this category included any seedling that matched a planted species that had reproduced in a site); (3) a seedling derived from a nearby source outside the restoration site; (4) a seedling or sprout that arrived in a root ball of a planted individual (presumably from a population at the source nursery).

Following the census, we surveyed the surrounding area to identify potential natural seed sources. Distances from nearby woodland remnants were estimated for all 50 plots to determine approximate minimum travel distances for each new species in every plot. Formal control plots (devoid of trees and shrubs) could not be established because the area surrounding the restoration site was mowed. As a substitute, we compared results informally with censuses taken on another nearby landfill to infer differences between background levels of woody plant recruitment and the putative effect of adding trees and shrubs. The Brookfield Landfill, also located on Staten Island—within 4 km of the Fresh Kills Landfill, was closed in 1985. The 20-ha site, which borders a 105-ha forested reserve, was seeded with commercial grasses upon closure and has since received no maintenance. It is similar to the Fresh Kills Landfill in soil types and surrounding vegetation. We censused all woody plants in three 0.5-ha plots, corresponding to the total area of the Fresh Kills Landfill restoration.

Results

Summary of Natural Recruitment

The majority of individuals and 17 of the 18 species planted were surviving (Table 1). Growth estimates indicate that most trees had moderate increases in girth (0 to 50%) over the first season, whereas most shrubs grew substantially in height, about 60% on average. A low proportion (19%) of plants were reproductive; most were either too young or perhaps suffered transplant shock. This is reflected in the very slight recruitment directly attributable to the plantation (0.4%; Table 2).

After one year, natural recruitment had boosted the

Table 2. Census data for woody species naturally recruiting during the first season following installation of the Fresh Kills restoration.

Species	Origin	Total count	Distance (m)	Principal vector
Acer rubrum	native	14	228 (50)	wind
Ailanthus altissima	alien	65	299 (70)	wind
Albizia julibrissin	alien	47		wind
Baccharis halimifolia	native	64	162 (21)	wind
Campsis radicans	native*	19	124 (51)	animal
Celastrus orbiculatus	alien	77	131 (50)	animal
Comptonia peregrina	native	22	142 (21)	animal
Cornus stolonifera	native	2	215	animal
Crataegus sp.	native	1		nursery soil
Eleagnus commutata	native*	6		nursery soil
Juglans nigra	native	1		animal
Juniperus virginiana	native	1	397	animal
Liquidambar styraciflua	native	37	299 (55)	wind
Lonicera japonica	alien	2	124 (103)	animal
Parthenocissus quinquefolia	native	40	139 (51)	animal
Paulownia tomentosa	alien	1	179	wind
Populus tremuloides	native	29	143 (60)	wind
Prunus serotina	native	108	120 (47)	animal
Quercus prinus	native	1		animal
Quercus velutina	native	1		nursery soil
Rhus aromatica	native	1		animal
Rhus copallina	native	276	125 (52)	animal
Rhus glabra	native	86	133 (26)	animal
Robinia pseudoacacia	native*	34	121 (46)	wind
Rosa multiflora	alien	5	81 (45)	animal
Rosa sp.	native	2	115 (91)	animal
Rubus sp.	native	87	128 (53)	animal
Salix discolor	native	1	287	wind
Sassafras albidum	native	8		animal
Smilax sp.	native	6	141 (61)	animal
Toxicodendron radicans	native	26	121 (55)	animal
Vitis sp.	native	4	106 (41)	animal
	Total count	1074		

**Native to the U.S. but not to Staten Island (Buegler & Parisio 1982).*
Total count is the number of individuals censused throughout the plantation. Distance is the minimum mean travel distance (±1 SD) from the nearest identified seed source to each plot where a recruit was found. Species without a distance value arrived in nursery soils or from unknown sources.

plants to some attractive feature of the plantation. Censuses of the Brookfield Landfill, where trees and shrubs were never planted, indicate that some woody plants were recruiting. Nineteen species were found, only six of which were wind-dispersed (therefore, animal dispersal was occurring). Stem densities were relatively low however, 145/ha, compared with 640/ha at the Fresh Kills site. Judging by their sizes, approximately half of the recruiting plants were recent seedlings, and this roughly translates to an eight-fold lower rate of annual recruitment on the unplanted site.

Another comparison was afforded by an experimental woodland planted in 1976 on part of the Edgeboro Landfill, East Brunswick, New Jersey (Gilman et al. 1985). By 1990, this plantation had been invaded by a great many new trees, shrubs, and vines—mostly native, berry-bearing species, from nearby riparian forest remnants (Robinson et al. 1992). Stem density of recruits was about 3100/ha, or nearly three times that of the original planted trees and shrubs.

Discussion

Restoration programs are often trial-and-error endeavors, but firmer ecological bases are being developed. For example, recent studies indicate that the pace of restoration and the development of wildlife habitat increase with greater vegetation complexity (Gibson et al. 1985; Parmenter et al. 1985; Schuster & Hutnick 1987; McKell 1989). The natural value of revegetated landfills and similar highly disturbed sites could be greatly improved by landscaping with attention to this need for vegetative complexity. The prospects for using restored lands to enhance biodiversity are sufficiently strong to deserve attention (Bradshaw & Chadwick 1980; Cairns 1988;

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FRESH KILLS, NEW YORK

CHESTER COUNTY, PENNSYLVANIA

9

APPLYING AN ECOLOGICAL PERSPECTIVE TO THE ENGINEERING OF LANDFILL FINAL COVER REVEGETATION

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Introduction

Solid waste landfill facilities undergoing closure are giving increasing emphasis to the role of the vegetative layer in the overall success of the final cover system. This paper describes selected current revegetation research efforts, with the goal of defining methods in which research findings can be adopted by the engineering community. Benefits to the owner/operator and to the surrounding community can be achieved through the use of innovative approaches for revegetation at closed landfill sites.

Final cover vegetation plays a vital role in erosion control and protection of the final cover system. In addition to improving these functions, certain facilities are investigating alternative cover types (native vegetation) and the application of ecological principles to the closure system revegetation design. These efforts extend traditional final cover system improvement concepts in an attempt to achieve "ecological restoration" of closed landfill sites. The revegetation programs discussed in this paper emphasize the use of native vegetation in the landfill closure system to facilitate:

- Establishment of the vegetative layer as an integral part of the final cover through selection of vegetative species that are able to provide design improvement to the closure system.
- Reduction in costs associated with long-term maintenance at the facility by providing a vegetative cover that is adapted to local conditions and capable of surviving and thriving at the facility.
- Creation of wildlife habitat and/or passive community areas for recreation at the closed landfill facility.

Background

The premise of the revegetation research discussed in this paper is straightforward: ecological principles that are focused on the establishment of a dynamic and sustainable vegetative community can be incorporated into final cover engineering designs to enhance both the long-term stability of the cover system and to achieve ecological restoration at closed landfill facilities. Post-closure success of the final cover depends, in part, on the capabilities of the vegetative layer and its ability to survive, grow, and reproduce in the landfill environment.

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Role of Vegetation in the Cover System:

The use of vegetation for erosion control is a standard civil engineering practice. Vegetative cover aids in erosion control through rainfall interception; physical binding of the soil particles; decreasing the velocity of runoff; maintaining soil porosity; increasing infiltration versus runoff; and through transpiration of soil moisture (Gray and Leiser, 1982). Although the benefits that can be provided to an engineered system by a well-designed vegetative cover are understood, this layer typically receives less focus than the other cover system components in the engineering design. As increasing numbers of landfills in the United States undergo closure and face the prospect of 30 years of post-closure care, an increased emphasis should be placed on a healthy, end-use compatible vegetative layer as a means of maintaining landfill cover integrity with a minimal need for maintenance. Innovative research efforts at facilities emphasizing revegetation provided methods for incorporating improved vegetative types as part of the closure system design.

This paper discusses facilities that are researching the use of ecological principles in landfill engineering design. The practice of ecological restoration on so-called "derelict" land emphasizes the use of native vegetative species rather than introduced vegetative types. Native species are those that have occurred historically and naturally in an area; while the introduced species have been brought into the United States from European, Asian, African, and other countries. Reasons for introducing species in the past have included improved capabilities for erosion control, more resilient pasture grasses, and increased selection for ornamental purposes such as lawns.

Introduced Species:

Traditional MSWLF closure in the northeastern and mid-Atlantic regions primarily consists of establishing and maintaining a mixture of introduced herbaceous vegetation. In these portions of the country, introduced species typically consist of cool-season varieties, meaning that their major period of growth is during the cooler spring and fall months. Over the years, these introduced species of grasses and herbaceous cover (e.g., crown vetch) have been used for landfill closures because they are relatively inexpensive, widely-available, and can establish quickly on the final cover slopes.

Introduced species, while often adapted to local climatic conditions, may not be suited to the harsh stresses of the typical landfill environment. These species typically require fertilization, liming, pesticide application, and mowing to achieve a quality stand.. The high cost of maintenance needs to be balanced with the relatively low cost of initial establishment to evaluate the real cost of using an introduced grass cover type in a landfill closure.

Native Species:

Although introduced species have an established role in engineered slope protection systems, the role of native species generally has not received equal attention. For the purposes of the landfill closures discussed in this paper, native species include species that are typical of native grasslands, such as Switchgrass and bluestems. Native species, once established, can compete well in the low-fertility, droughty (dry) soils associated with closed landfill sites. To address increasing concerns with long-term maintenance costs and landfill end-use, the use of native vegetation is being investigated for its capability to provide a more successful, and sustainable vegetative layer with a higher habitat value.

Native species have not been used widely in landfill closures in the past, likely because they can be more difficult to seed and are more costly than introduced species. However, because native species are naturally adapted to a local environment, their reduced maintenance requirements should result in significant long-term cost savings for owners/operators. One basic goal of current revegetation research efforts is to study and document the long-term capability of native species to compete and survive on closed landfill sites.

Overview of Current Revegetation Investigations

The majority of this paper is focused on the conduct of revegetation investigations at the New York City Department of Sanitation (NYCDOS) Fresh Kills Landfill in Staten Island, New york. Another facility discussed briefly in this paper is the Chester County Solid Waste Authority (CCSWA) Lanchester Facility in Pennsylvania. SCS Engineers is developing the engineering design of closure systems for each of these facilities.

Revegetation research initiated by the NYCDOS at the Fresh Kills Landfill is focused on the use of native species for landfill closure and the development of methods for successfully establishing these species as part of the 2,000-acre facility. Pilot projects have been established at the landfill to investigate the role of native herbaceous vegetation, shrubs, and trees as components of a successful landfill closure and ecological restoration at the site.

The field-scale pilot projects have been designed, monitored, and evaluated by various researchers under the guidance of NYCDOS. Experimental methods have been described in conservation biology journals and other scientific publications. The purpose of this paper is to summarize these experiments and their findings (to date) as they relate to the engineering design of the landfill final cover.

The most recent series of investigations at the Fresh Kills Landfill, conducted by scientists from Rutgers University in New Jersey (Handel and Ehrenfeld, 1991), are examining the ability to reclaim highly disturbed land using native vegetation and the principles of restoration ecology. The investigations by Rutgers and those conducted by the final cover design team can be categorized as they relate to the following engineering/revegetation design questions:

- Economic and design issues - Will the investment in quality soils and vegetation at closure result in significant long-term savings through a reduction in post-closure maintenance costs? Can a low-cost vegetative layer be designed to achieve the performance objectives for the landfill final cover system?

- Regulatory considerations - Are alternative cover types capable of meeting design objectives such as erosion control and establishment of the required density of vegetative cover? Do proposed alternative cover types (specifically woody vegetation) achieve design objectives, including protection of the final cover system?

- Ecological restoration end-use - Does the use of alternative vegetation conform with the end-uses designated for the facility?

The subsequent three sections of this paper focus on the pilot projects being conducted at the Fresh Kills Landfill and their ability to provide answers to the above questions. The sections are divided into an introduction, an overview of field pilot projects, and a discussion of the impact of the revegetation investigations on the design decisions for the facility.

Budget and Design Issues

Introduction:

The capital cost of installing landfill vegetative cover needs to be weighed against the long-term financial commitment involved in maintaining the cover system. As previously discussed, characteristics of native grasses can make them more difficult and more expensive to establish than the introduced species. Pilot projects have been initiated for evaluating various vegetative establishment methods, species mixtures, and the use of alternative soil amendments to improve cover quality. Long-term monitoring of these pilot projects will allow comparison of the capital expenditure (establishment) and the post-closure care (maintenance) of the different cover systems. Considerations for the establishment of woody vegetation are discussed later in this paper.

Pilot Projects - Herbaceous Cover:

Before vegetative enhancements, such as woody vegetation, could be considered at the Fresh Kills Landfill, successful methods for establishing a native herbaceous (grass) cover needed to be developed. Specific technical constraints at the facility included expected low maintenance, no irrigation, fairly steep (2.5:1 or 3:1) slopes, exposure to frequent high winds, and exposure to cold and heat. These factors increase the likelihood of dry, low fertility conditions, which result in a corresponding increase in stresses to the vegetation.

In order to respond to landfill conditions, native grasses were selected as the most-suited cover type. Due to the difficulties associated with establishing native grasses on slopes, the pilot projects were focused on developing successful seeding techniques and species mixtures. The native grasses used in this research are warm-season grasses (the name is derived from the fact that the primary period of growth of warm-season grasses is during the warmer, summer months). The wide spread use of warm-season native grasses generally has not been adopted on landfills because they can require two years to develop a stand density capable of providing adequate erosion control. As previously discussed, "typical" landfill revegetation in this region uses the introduced (cool-season) grasses.

Pilot projects included:

- Use of alternative seeding equipment. The "awn" on some warm-season grass seeds can result in "fluffy" seeds which are difficult to hydroseed. Improper addition of the seeds to the slurry can result in uneven distribution, mixture, potentially clogging the hydroseeding equipment. Native grass test plots were established using drill seeding, broadcast seeding, and land imprinting to evaluate the success and projected cost of alternative seeding techniques.

- Alternative hydroseeding techniques were investigated. The rate of addition of the warm-season grass seeds to the hydroseed slurry was evaluated to determine if clogging of equipment could be prevented. In addition, the use of a two-step hydroseed procedure (hydroseed followed by mulching) was compared to the traditional one-step procedure (simultaneous hydroseed and hydromulch).

- Use of a variety of seeding mixtures. The primary concern with warm-season grasses on landfill slopes is the time period required for germination. Test plots using warm-season native grasses in combination with varying percentage of cool-season grasses were established. The goal was to provide a rapid cover via the cool-season "typical" landfill grass and a long-term cover of warm-season grasses. The warm-season grasses included Little Bluestem, Big Bluestem, Indian grass, Sand Lovegrass, and Switchgrass. The cool-season companion grasses included Annual Rye and Sheep Fescue.

- Evaluation of alternative mulch materials. Hydromulching and hay mulching were compared, as were various tackifiers and erosion control netting products.

Pilot Projects - Soil Amendments:

Initial evaluation of soil amendments at the Fresh Kills Landfill involved a qualitative analysis of the benefits provided by supplementing the organic content of the topsoil layer. Composted leaf mulch was added to the pilot project soils to assess the effects on seedling germination, growth, and density of herbaceous cover. When compared to a control plot, the treated pilot project areas showed a definite improvement in both germination and seedling survival. Because an on-site source of compost is available at the Fresh Kills Landfill, studies evaluating the relative costs and benefits of various types of organic amendments were not conducted.

At the Lanchester Facility administered by the CCSWA (Pennsylvania), a variety of composted materials are locally available. To date, SCS Engineers has investigated the qualities and costs of spent mushroom compost, yard waste compost, and sewage sludge compost as part of a manufactured topsoil at this Facility. Each material was surveyed in a desk top study relative to reported nutrient content, organic content, cost, and horticultural value.

The focus of this paper is on revegetation; therefore soil pilot projects are not reviewed here. However, the successful establishment of vegetative cover cannot be separated from the issue of the quality and depth of the erosion layer ("topsoil" layer) soils. With respect to revegetation and long-term sustainability of the final cover, one of the most critical aspects of the closure system design is the selection of the soils component of the cover system. The erosion layer soils provide the primary moisture reservoir, rooting zone, and nutrient source for the vegetative cover. The potential for decreasing vigor of the final cover vegetation increases where an insufficient depth or quality of soil is installed at closure.

Note that the 40 CFR Part 258 (Subtitle D) regulations present minimal requirements for the landfill final cover soils. The closure criteria call for installation of a final cover system that is designed to minimize infiltration and erosion, and require a "minimum of 6 inches of earthen material that is capable of sustaining native plant growth." A research project focused on comparing vegetative survival for landfill facilities closed with this minimal requirement versus those closed with an improved soil quality and depth would benefit those facilities that have not yet undergone closure.

Design Impact Evaluation:

The revegetation investigations focused on improving the quality of the herbaceous cover and the cover system soils. Evaluation of the pilot projects resulted in the development of revised specifications at the Fresh Kills Landfill and the Lanchester Facility. The basic findings of the pilot projects were that 1) native grasses could successfully be established from seed in large-scale plantings, and 2) the quality of the topsoil directly affects the success of the vegetative cover. The following pilot project results were used to adjust the specification and seeding procedures at the Fresh Kills facility:

- The results of the native grass plantings demonstrated that plots using only warm-season grasses were not successful, as the loss of soil fines and erosion on landfill slopes during the first year of closure were too high to allow future seedling germination. Plots which incorporated a companion grass (cool-season) were successful provided that a low seeding rate (40 to 50 pounds per acre) was used. Low seeding rates of the companion grass prevented overshadowing of the warm-season grass seedlings. The current revegetation procedure at the landfill calls for a combination of warm-season grasses and an overseeding with the companion grass component.

- With respect to planting techniques, it was found that successful hydroseeding of warm-season native grasses could be accomplished, achieving both economic and design objectives for closure. The cost of purchasing debearded (awn removed) seeds was recovered through the use of hydroseeding, a relatively low cost seeding technique. The technique for mixing the hydroseed slurry was adjusted to accommodate a slower rate of addition of the seeds to the slurry. In addition, the one-step process of hydroseed and hydromulch is no longer used, having been replaced by a two-step hydroseeding and mulching process to improve soil to seed contact.

- Other successful planting techniques included land imprinting and broadcast-and-track seeding. Land imprinting requires specialized machinery. Broadcast seeding is a widely-available technique capable of seeding large areas. Standard broadcast seeding specifications were modified as part of the test process to include tracking (using low-ground pressure tracked equipment to incorporate the seeds lightly into the soil surface, improving soil to seed contact) following seeding. This approach enhanced seedling germination as well as aided in physical soil erosion control during the germination period.

- The use of hay mulch with a tackifier was adopted to increase soil moisture retention and protection from wind and water erosion.

- The minimum organic content of the topsoil layer was increased to five and then to seven percent. The specification was expanded to allow the use of compost materials rather than limiting the organic amendment to peat humus. Testing requirements for the topsoil and amendments were increased to evaluate the soluble salts, potential contaminants, nutrient content, and other aspects of the quality of the selected compost amendment.

Regulatory Considerations

Introduction:

As required by the regulations, the final cover vegetative layer should provide erosion control and protection of the final cover system. Test plots designed to examine the germination rate and density of alternative (native) herbaceous vegetation and the use of woody vegetation on closed landfill slopes are being evaluated. The use of non-traditional cover types to meet other objectives (e.g., post-closure care cost reductions, ecological restoration) will only be successful where the alternative vegetation meets the regulatory performance standards.

Pilot projects evaluating the success of different herbaceous cover types in the landfill environment were discussed earlier. The intent of this section is to address the general regulatory prohibition concerning the use of woody vegetation on landfill final cover systems. A basic objective of the work being conducted at the Fresh Kills Landfill is to demonstrate the benefits of woody vegetation for use in landfill closure systems, and to evaluate the ability of woody vegetation to provide protection to the underlying cover system.

States generally require owners and operators to prevent the establishment of woody vegetation on the landfill final cover. From a regulatory perspective, the primary concern is the potential for woody vegetation roots to penetrate the landfill cover system and allow water to infiltrate into the underlying waste. An increase in infiltration would increase leachate generation at the facility. Additional concerns with woody vegetation include the potential for 1) the weight of the vegetation to cause a downward, destabilizing stress and 2) windthrow, or the action of wind in large storms causing a twisting of the roots, resulting in either destabilization of the final cover soils or a possible uprooting of the vegetation (Grey and Leiser, 1982).

The potential negative impacts of woody vegetation are given significant attention, whereas the positive factors provided to the landfill slope stability by woody vegetation are less frequently presented. In requiring the removal of woody vegetation from closed landfills, the capabilities of this type of vegetation in slope stability also are removed. According to Shields and Gray (1992), woody plants help to prevent mass-movement and shallow sliding in slopes. The positive role that woody vegetation can play in slope stability include mechanical reinforcement of a soil and control of the soil moisture regime.

Pilot Projects - Root Penetration Test Plots:

Root penetration test plots have been established at the Fresh Kills Landfill to specifically monitor the behavior of roots in the final cover soil system. The pilot projects were established in an area with approximately twenty-four to thirty inches of soil over a clay infiltration layer. The June 1992 plantings of woody vegetation included a total of 17 shrub and tree species installed on a selected landfill side slope, with individuals of each species planted at varying points along the slope gradient to account for differences in moisture content and soils. The 17 species were selected for their variety of "typical" root growth patterns.

In the fall of 1992, ten individuals of each of the seventeen species were excavated to examine the root architecture. No root systems were observed to be in contact with the clay layer at that time. An additional 340 individuals are targeted for excavation in the fall of 1993, and the two-year study results will be available in 1994.

Design Impact Evaluation:

Much of the ecological restoration research being conducted at the Fresh Kills Landfill (see below) involves investigation of low-cost successful methods for the establishment of woody vegetation on the landfill cover. Rutgers University researchers anticipate that root penetration will not pose a problem, due to the ability of root systems to adapt their growth structure to respond to site soil conditions. The results of the root penetration studies will be evaluated to determine any final cover design alterations that are required to support the restoration objectives (e.g., greater soil depths).

Ecological Restoration End-Use Objectives

Increased attention has been given to the proposed end-use of closed landfill sites. End-use is an especially important issue where significant land use pressures have reduced available open space. For this reason, facilities in the northeast, mid-Atlantic and other regions have begun to look at the resource potential of closed landfills.

There are many types of end-uses that have been considered and implemented at closed landfill sites across the nation. Facilities have used closed landfills for leaf and yard waste composting operations; baseball fields and other active recreation facilities; buildings; passive recreation facilities; and other uses. One end-use being researched at the Fresh Kills Landfill through the series of pilot revegetation projects is the restoration of native habitat to the landfill. Establishment of part of the 2,000-acre site as an ecological community will provide vital links (corridors) between the facility and surrounding wildlife refuges and tidal/freshwater wetlands. The establishment of native habitat would provide passive recreational opportunities for the surrounding community.

One major component of ecological restoration at the Fresh Kills Landfill is the development of techniques to establish a self-sustaining native forested community. Current regulatory concerns with the establishment of woody vegetation on closed landfills were discussed above. The demonstration plantings at Fresh Kills are examining whether a cost-effective method for establishing a desirable, self-sustaining, native woodland community can be achieved through the closure planting design.

Pilot Projects - Woody Vegetation:

In addition to the root penetration pilot projects discussed earlier, woody vegetation pilot projects at the Fresh Kills Landfill include:

- Field investigations to test the feasibility of introducing woody vegetation by direct seeding, including studies of the effects of herbivores on woody vegetation seeds and seedlings. The cost savings that could be achieved via establishment of trees and shrubs from seeds (as opposed to planting of nursery-grown shrubs and saplings) would increase the feasibility of restoration at the facility. For the pilot projects, seeds from 27 species of native trees and shrubs were collected and planted (over 15,000 seeds in total). Evaluation of the findings resulted in identification of 8 species that are well-suited to establishment by direct seeding, and an additional 8 species that would likely germinate successfully with some seed preparation prior to planting. The physical preparation and quality of the soil substrate plays a role in successful seedling establishment (DeSteven, 1991). The effects of herbivores on the seeds and seedlings were evaluated to determine any protective measures that would be required in conjunction with future plantings.

- Evaluation of forest restoration and the reproductive ecology of woody vegetation on closed landfill sites, and investigations of methods for the stimulation of woodland restoration. The ability to restore woodland in a low-technology and low-cost manner is dependent on the ability of the vegetation to reproduce and spread in the landfill environment. Reforestation of entire portions of the landfill using traditional landscape techniques would be prohibitively expensive. The pilot projects are investigating the establishment of clusters of plantings (rather than higher density continuous plantings) for their ability to serve as seed sources and bird/mammal attractants for the encouragement of plant reproduction. Clusters of different sizes, distribution, and species composition have been established (fall 1992) and will be evaluated for their ability to achieve successful, low-cost restoration (Robinson, et. al., 1991).

Because a landfill represents an artificial system, the absence of natural soils and an existing ecological community makes it difficult to predict the ability of a man-made plant community to be self-sustaining. The Fresh Kills pilot projects investigate the cost and the methodology required for successful ecological restoration at the facility. The ecological findings of the studies will be published by Rutgers University researchers following evaluation of the studies.

Conclusion

The primary objective of a landfill revegetation program is to function as part of a stable cover system, minimizing erosion and soil loss. Findings of revegetation research indicate the importance of integrating the planning and design of the revegetation program with the other components of the final cover, especially the final cover soils layers. Vegetation is a component that can work in conjunction with the other layers to improve the overall success of the closure and reduce costly maintenance during the post-closure care period.

Pilot projects are being conducted that will increase the available design standards for achieving low cost and successful closure projects. It is hoped that ecological principles based on self-sustaining natural communities can be integrated in engineering design, thereby expanding options for achieving design, regulatory, and end-use objectives at closed landfill facilities.

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TO CATHY STEWART

THE PLANT COMMUNITIES ON FOUR LANDFILL SITES, NEW YORK CITY NEW YORK

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ABSTRACT

The plant communities at four landfill sites, New York City, New York, were examined during the summer and fall of 1983. The vegetation at each site was sampled by the quadrat method to determine species composition and dominance. Artemisia vulgaris and Phragmites communis were the dominant species at all sites. Additional members of the gramineae and compositae were locally dominant or common at each of the four study sites. Fires of high intensity in the Phragmites dominated areas may be the most important factor in maintaining the present assemblage of vegetation. Other factors of importance are: time of disturbance; proximity to seed sources, and species providing seeds; soil texture; local variations in topography; presence of a permanent or seasonally high water table, drought; the nature of the fill material; the activity of small mammals, especially meadow voles and rabbits; allelopathy; local mowing; and local soil disturbance by motor vehicles. In the absence of defined maintenance procedures, the future composition of the vegetation at each landfill cannot be predicted with certainty.

INTRODUCTION

The plant communities at four landfill sites in New York City, New York, were examined during the summer and fall of 1983. All four landfill sites were constructed on land formally occupied by salt marsh species. The four landfill sites include one active site, the barge-fed Fresh Kills Site on Staten Island, one "inactive" Site; the Pennsylvania Ave. Truckfill; and two recently closed landfills, the Idlewild Truckfill and Marine Park Truckfill. Inactive sites may receive from 1000 to 2,000 tons of debris/day; closed sites receive no additional fill materials (11).

The Idlewild Truckfill site, Queens County, New York, (Site 1) is located south of 140th Ave., North of Rockaway Blvd. east of Brookville Ave., and east of Springfield Rd.. This site, encompassing 133 acres, was used for construction wastes from 1969 to 1974. Sand from the site was used as cover material. This site was closed in 1974, and was re-vegetated by natural seed sources.

The Marine Park Truckfill Site, (Site 2) is located in Brooklyn, west of Flatbush Ave. and Floyd Bennett Field. The southern portion of the site is bordered in part by Rockaway Inlet. This facility

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comprising 726 acres, (of which 184 are undeveloped park land) was used for construction waste. Cover material was salvaged soil and sand. After the site was closed, natural vegetation was allowed to invade the area.

The Pennsylvania Ave. Landfill, (Site 3) comprising 110 acres, is located in Brooklyn directly south of the Fountain Ave. Landfill. It is bordered to the north by the Belt Parkway, to the east by Hendrix Creek, and to the south by Jamaica Bay, and the west by Fresh Creek. Opened in 1956, this landfill was relegated to inactive status in 1974. The Pennsylvania Ave. Site, classified as "inactive" receives from 1000 to 2000 tons of demolition debris per day per year. At the present time the site consists of two plateaus; 40 feet high, and 80 feet tall respectively. The final plan calls for contouring with construction waste to plateau levels of 80 and 165 feet respectively. Cover material for this landfill has been sand and " approved soil". When this site is closed it will be managed by the Gateway Unit of the National Parks Service.

The Fresh Kills Landfill, (Site 4) comprising 2200 acres, presently handles more than one half of the city's total refuse. This site was opened in 1948. Clay is used as cover material here.

Construction and depth of the materials placed in the land fills is similar. Prior to 1962, every 10' to 20' of refuse was covered with 4" to 6" of soil. After 1962, six to nine inches of approved soil were used to cover every 10' to 20' of refuse. Approved soil or approved cover material consists of a mixture of gravel, sand, silt, a loam and clay. This soil classification conforms to ASTM Standard D-2487-69 "Classification of Soils for Engineering Purposes" (11).

The Department of Sanitation, City of New York, has provided outside contractors with specific instructions for reseeding of their active landfills. Mulch will be applied to all seeded areas. Perennial ryegrass, timothy, Kentucky 31 Fescue, Sheep Fescue, Reubens Cana Bluegrass and little Black Sunflower seed will be used to revegetate the area at 125 lb./acre. To stimulate and enhance seedling developement, 10-10-10 Fertilizer at 800 lbs./acre, and wood fiber mulch at 1500 lbs./acre will be applied during seeding. Seeding will occur between March 1 and April 15th or Sept. 1 through October 31. Steep sides of landfill sites will be held in place with Jute Mesh (13).

The present study was conducted to describe the plant communities on four landfill sites in New York City, New York. A second objective was to record the phenology (time of flowering), abundance class, and dominance of species occurring at the four landfill sites.

MATERIALS AND METHODS

Thirty (one meter^2) quadrats were established at each of the four landfill sites, and abundance classes for each species was recorded. Sampling was initiated in June, 1983 and continued at six-week intervals terminating on October 5, 1983. Phenology (flowering date) and abundance classes were established for each species at each of the four sites from June to October. Abundance classes for each species at each study site are presented in Table1.

RESULTS AND DISCUSSION

IDLEWILD TRUCKFILL

Artemisia vulgaris is the dominant species in the upper roadside border of the Idlewild Landfill while Phragmites is dominant in the inner lower portion of this site. Phragmites covers more than three fifths of the landfill. The other species found here are unimportant (Table 1).

MARINE PARK TRUCKFILL

Phragmites communis is the dominant species at the Marine Park Landfill. Phragmites produces new growth in early April and is the dominant plant at this site. Other species of importance include Festuca rubra, Poa spp., Agrostis alba and Agropyron repens. By mid August, Ambrosia artemisiifolia is the dominant species on disturbed ground paralleling the sidewalk at Flatbush Ave.. Artemisia vulgaris is common in the mown path cut through Phragmites. Other important species on disturbed portions of the Marine Park Truckfill are noted in Table 1 by an *. Tree species are infrequently represented by Prunus serotina, Populus tremuloides and Ailanthus altissima. Myrica pennsylvanica, a frutescent species, is an occasional occupant of this site.

THE PENNSYLVANIA AVENUE TRUCKFILL

Artemisia vulgaris is the dominant taxon covering most of outer berm at the Pennsylvania Avenue landfill. Phragmites communis covers 100% of the portions of the southwest portion of the landfill. Bromus japonicus is another conspicuous member of the herbaceous stratum especially along the disturbed roadside during May and June. Salt marsh species occur on the border of Fresh Creek. These plants, listed in order of their elevation above datum, (mean low tide level) are: Spartina alterniflora, S. patens, Iva oraria, and Solidago sempervirens. Phragmites, favoring open wet areas, but not highly saline areas, is not a salt marsh plant and will not grow in waters where salinity exceeds 10^{o}/oo for long periods of time. Like the other landfills, few trees are found here. These include: Prunus serotina, Ailanthus altissima, Morus alba and several planted ornamental species. The ornamentals are located on the beltway border.

By early August, Panicum virgatum is in fruit and flower. This species is the dominant plant on the lower half of the southwest portion of the landfill berm. Disturbed roadsides on the landfill are vegetated by Erigeron canadensis while the center of the road is populated by Agrostis hyemalis from August to October.

The roadside border is brightened by fall-flowers e.g. Aster ericoides and an occasional Solidago sempervirens. Solidago will flower through October; some individuals will flower in November. Digitaria sanguinalis and Ambrosia artemisiifolia are additional dominant members of the disturbed roadside community.

FRESH KILLS LANDFILL

The Fresh Kills Site is the largest most active landfill site. The recently constructed berms are subject to severe erosion, which hinders colonization by plants. Common species invading the berm include: Helianthus annuus, Polygonum spp., Artemisia vulgaris, Erigeron canadensis, and Phragmites communis. In September, Artemisia is dominant on portions of the berm, and is the dominant plant between the berm and the cyclone fence bordering the site. Another dominant taxon, Phragmites, often forms dense thickets in certain areas. Spartina alterniflora occupies land that is inundated daily by the tides.

Although the dates of final closure, size of the landfill site, and maintenance techniques vary from site to site, two species, Artemisia vulgaris and Phragmites communis are dominant at all sites. Artemisia colonizes a site more rapidly than Phragmites, favoring drier soil conditions than tall reed. Phragmites eventually assumes and maintains dominance, where the water table is near or at the surface of the ground for long periods of time.

The vegetation on the landfill sites is similar to that on vacant lots in New York City (4). Artemisia vulgaris is a common plant on vacant lots in the Bronx, New York. Artemisia is accompanied by seventy two weedy species, many of which are similar to those observed on landfills. Species common to vacant lots and landfills include: Phragmites communis, Polygonum spp., Trifolium spp., Helianthus annuus, Erigeron canadensis, Melilotus alba, Ambrosia artemisiifolia, Chenopodium album, and many others (4).

Personal observations in a variety of study areas and copius references in the literature indicate that there are a multiplicity of factors responsible for the present assemblage of vegetation at each landfill. These factors include the time of disturbance (2,4), fire (7,8,9), The nature of the fill material (3), soil texture (9, 10), presence of a permanent or seasonally high water table, drought (9), proximity to seed sources (3), local variations in topography (3), the activity of small mammals, especially the girdling activity of the meadow vole and selective feeding on stems and twigs by rabbits during severe winters (6), allelopathy (5,8), local mowing (10), and local soil disturbances by motor vehicles (10). The importance of the aforementioned factors in maintaining plant populations and or affecting plant succession has been discussed in detail in the preceeding references. The importance of each factor is variable since not all factors exert the same amount of influence each year or each season (9).

Fire has played an important role in maintaining the present assemblage of species. Data from the N.Y.C.F.D. for a five year period, 1978 through 1982 indicates that fire frequency at landfill sites is high, ranging from 3 fires in 1978 to 50 fires in 1979 (12). March and April are the months when fires are most frequent. During March, April and May, clear warm days with low relative humidity coupled with strong winds will produce conditions condusive to severe fires, especially where *Phragmites* is dominant. Dry dead culms of *Phragmites* may reach 10 feet tall, and provide excellent fuel for fires. Personal observations on Canarsie Pol and Floyd Bennett Field indicate that all shrubs and most trees are killed by fire in *Phragmites* dominated areas. Fire will probably always be present on landfill sites and is a very important factor in maintaining the present assemblage of vegetation.

The topography at each site is varied. The steep sides of the man-made berms produce highly unstable soil. The berms are exposed to the sun and wind and dry out more rapidly than level portions of the landfill. Rain caused erosion on the berms at the Fresh Kills Site, washes soil from the berm to its base. Plants have a difficult time getting established under these conditions. *Helianthus, Ambrosia* and *Polygonum spp.* are common berm colonizers. These annuals are replaced by *Artemisia vulgaris*, an aggressive perennial that is well adapted to drought and sterile soil..*Artemisia* may produce allelopathic products, that prevent or inhibit the invasion by other species.

The Gramineae and Compositae that are found on or near landfills produce a prodigious amount of wind-carried seeds. These taxa can rapidly invade the landfills. The few invading trees and frutescent species also produce wind-blown seeds e.g. *Populus* and *Ailanthus*. In addition, birds have carried seeds of *Prunus, Rhus*, and *Myrica* to the landfills. Germination of seeds may be enhanced after the seeds have passed through the bird's digestive tract.

Variability in the numbers and kind of species at each site might reflect: seasonal availability of seeds; annual variation in weather, extreme drought and local variation in soil and disturbance. These aforementioned parameters are probably responsible for the mosaic of plant communities that are found at each study site (9, 10).

Another factor influencing species composition is the type of fill material placed at each landfill. For example, a mixture of cement, plaster, gypsum, and lime may produce a higher pH in certain portions of the site. The higher pH might reduce nutrient availability which might excluding certain species favoring *Phragmites* (3).

Data in the present study indicate that few woody species have been successful invading each study site. The oldest site, the Marine Park Landfill,is dominated by *Phragmites*. Frequent *Phragmites* fires may produce temperature high enough to kill large trees, a speculation verified by observation of fire killed birch, cherry and poplar trees in a *Phragmites* dominated portion of Floyd Bennett Field in June, 1983. Above ground growth of bayberry,*Myrica pensylvanica*,was also destroyed by this fire; however, *Myrica* produced copious root sprouts after this burn. Observations by the author of severe fires in brackish and freshwater marshes in the southeastern United States in abandoned rice fields have prevented arborescent species from invading these areas (1). Future vegetation at the Marine Park, Penn Ave., and Idlewild will probably be similar to the vegetation present at these sites today if fires are allowed to burn unchecked in the future.

Many old field species and marsh species are common at the landfill sites. Dominant species are somewhat similar to the vegetation observed on abandoned lots in the Bronx, New York (3), on the roadsides of the Long Island Expressway within New York City (10), yet differ from species on old fields in New Jersey (2), or Hempstead Plains, Long Island, New York (10).

It is difficult to predict the future vegetation of each landfill. If the crowns of the Pennsylvania Ave. and Fresh Kills landfills are seeded and maintained by mowing, grasses will dominate these areas. The steep sides of the berms at the Fresh Kills Landfill are unsuited for mowing. Artemisia may probably assume early dominance on the berms at the Fresh Kill landfill. Succession to a shrub or shrub-tree climax on these areas may be slow. Areas where Phragmites dominates today may well be dominated by Phragmites in the future, especially if severe fires continue to ravage the area. With a multiplicity of factors repsonsible for the present assemblage of vegetation, and the uncertainty of how these areas may be maintained in the future, succession in a directional sense is uncertain. Unpublished work by the author at Fort Tilden, New York and observations at Floyd Bennett Field, New York represent areas similar to the landfill sites and may provide clues to successional trends. On higher drier areas that are protected from burning, shrubs, e.g. Myrica pennsylvania, Prunus maritima, and Rhus toxicodendron may become established as they have at nearby Fort Tilden and Floyd Bennett Field. Prunus serotina, and Amelanchier canadensis may follow frutescent species. Populus and Ailanthus may be locally dominant. However, succession with an oak dominated hardwood forest may never occur or may take far longer than succession on fallow farmland in near-by rural New Jersey(2).

Table 1. Species composition and dominance as determined by abundance class for species on four landfill sites, New York City, New York. See introduction section for site location. Data were collected in late June early August and late September, 1983.

Species	June Study Sites 1	2	3	4	August Study Sites 1	2	3	4	September Study Sites 1	2	3	4
Artemisia vulgaris	5	1	5	3	5	2	5	5	5	5	5	5
Phragmites communis	5	5	5	4	5	5	5	5	5	5	5	5
Agropyron repens	2	2		2	2	3		2	2	2		1
Apocynum cannabinum	2				2							
Helianthus annuus*	2		3	4	4		2	4	2			2
Polygonum cuspidatum	1				1				1			
Asclepias syriaca	1				1							
Daucus carota	1				2				1			
Melilotus alba	2		1	2	2		1	1	1			
Melilotus officinalis*	1				2							
Ambrosia trifida*	1				1				2			
Panicum virgatum		1	2		2	2	5			3	5	
Andropogon scoparius		1				1				2		
Bromus japonicus		2	4	2				1				
Allium vineale		1										
Bromus mollis		1										
Poa elatior		4				3				3		
Poa compressa		4				4				4		
Agrostis alba		4				4				4		
Cenchrus tribuloides*						1				1		
Linaria vulgaris*		1										
Rumex acetosella*		2										
Agrostis hyemalis			1			2	5			2	5	
Panicum lanuginosum*						2				2		
Triplasis purpurea*						3				3		
Heterotheca subaxillaris*		2	1			4	1			4	2	
Ambrosia artemisiifolia*			1			1	2	1		4	3	2
Erigeron canadensis*			1	3		1	3	1		3	2	
Digitaria sanguinalis*			1			2	2			3	3	
Eleusine indica*						1				3		
Festuca rubra		5				5				4		
Lepidium virginicum*			1									
Chenopodium album*			1				1				1	
Polygonum spp.*			3	4			2	3			2	2
Xanthium echinatum*			1				1				1	
Erigeron annuus*			1									
Setaria spp.*				1			1	2			1	2
Aster ericoides*								1			1	4
Convolvulus sepium				1				1				1
Fagopyrum sagittatum								2				2
Lactuca scariola*				3				2				1

* indicates species occupies disturbed soil

Abundance Class

1 rare or from 1 to 20 percent
2 occasional or from 20 to 40 percent
3 frequent or from 40 to 60 percent
4 common or from 60 to 80 percent
5 abundant or from 80 to 100 percent

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On the maximum extent of tree roots

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ABSTRACT

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Based on literature reports, personal communications and our own observations, maximum vertical and radial root extents were tabulated for various woody species, primarily forest trees and shrubs, and horticultural trees. Data were summarized for 49 families, 96 genera and 211 species, as well as for forest stands composed of mixtures of species. These data demonstrate the inherent capability of many species to develop deep or far-reaching roots in the absence of restrictive soil or substrate characteristics. These data also suggest that extensive roots may play a more important role in uptake of water and nutrients than indicated by their density alone, and that actual, rather than assumed, root extent must be evaluated on a site-specific basis to provide realistic estimates of ecosystem properties and processes.

INTRODUCTION

The downward penetration of tree roots is commonly limited by mechanical impedance, by anoxia, by dry subsoils or, in cold regions, by very low soil temperatures or permafrost. The first two are widespread in soils of recently glaciated regions of Europe and North America. Most earlier studies of tree roots were conducted on such soils, giving rise to generalizations about the inherent rooting depth of species that still persist in the literature.

Soils with poorly aerated or dense layers or that are shallow over impenetrable bedrock occur in all climatic regions. The origin and location of such barriers are diverse. Commonly, they act either through (a) mechanical effects, preventing root entry or survival; or (b) some degree of poor aeration, resulting from slow hydraulic conductivity in combination with topographic and precipitation features. The latter (b) may be continuous, seasonal or episodic, but the two types of barriers often occur together. Their effects may be either absolute, preventing root entry or survival, or restrictive in various ways, such as sharply reducing root numbers, maximum size or longevity. Where aeration per se is not controlling, however, roots that penetrate a thin or discontinuous barrier may proliferate below.

In most forest soils studied, the number, length or surface area of fine and very fine roots (however defined) diminish rapidly from the surface or near-surface layers downward. With some important exceptions, most literature reports have been based on shallow (less than 1 m) pits or sampling depths which could not reveal any deep penetration or secondary increase in fine roots.

Emphasis on roots in the surface 10–100 cm is to be expected given the roles of holo-organic or organic-enriched layers in water entry and storage, in retention and mineralization of nutrients returned in plant litter and in initial establishment of all non-epiphytic species. This emphasis is reinforced by nutrient concentration data and, in the USA, by many empirical relationships (Carmean, 1975) between site quality and thickness or other characteristics of the surface layers.

The density of absorbing roots (number, length, etc, per unit soil volume) strongly affects initial rates of water and nutrient uptake and likewise competition among plants with roots in the same soil volume (Sands and Nambier, 1984). Density or derived values figure in attempts to model uptake rates (Barber, 1984). Long before such evidence was available, however, the relative contribution of a soil layer was assumed to be in some degree proportional to its fine root density. This assumption persists despite a long history of contrary evidence, such as the early observations of Partridge and Veatch (1932) and Viehmeyer and Hendrickson (1938), Gardner's (1964) emphasis on the presence rather than numbers of roots as influencing water uptake from a given soil volume, and comparative studies of tracer uptake (Ogus and Fox, 1970).

An unfortunate consequence of the above assumption, however, is an exclusive attention to the upper soil layers, usually to depths of less than 1 m, in most studies of nutrient sources, sinks and losses. With some exceptions, both the guiding concepts and techniques employed still ignore possible influences of deeper soil layers. This is surprising in view of the well-documented importance of deep roots in water uptake, as noted later.

Likewise, the role of far-reaching lateral roots in water and nutrient uptake is usually ignored except with arid-land species, yet a widespread root system is a means of exploiting sparse or irregularly distributed resources and, as a practical matter, may demand wider borders to isolate experimental or study plots than generally considered sufficient.

The purpose of this review, then, is to demonstrate the great vertical and radial distances to which roots of many species extend in favorable circumstances and to suggest that root extent must be actually evaluated on a site-specific basis, rather than assumed, if nutrient cycling or forest ecosystem studies are to be realistic.

PROCEDURE

We compiled accounts of what appear to be the greatest known depths and radial extent of roots of tree species and some wildland shrubs. Three sources were drawn upon:

(1) other reviews, largely reporting evidence from observation or excavation;

(2) published accounts of original research based on observations, excavations or soil cores, or on tracer uptake or measured changes in soil moisture;

(3) unpublished evidence, largely based on observations and excavations, either by us or by others who, in the main, were known to us.

We omitted as commonplace values of less than 1.5 m depth or 7.0 m radius except for young trees or as smaller values brought to notice otherwise unremarked species, substrates or methods. Probably all large tree species exceed these minima under favorable conditions. We omitted 'average' or typical values wherever maxima were given. An additional number of values were omitted because species or vegetation type were unknown or because of other uncertainties, or because they essentially duplicated listed values.

Occasional reports refer to actual length rather than radial extent of lateral roots. These were omitted, or rescaled from the diagrams given, or are specifically identified where included in Table 1.

Descriptions of tree size or age and soil characteristics in the original references were highly variable in detail or sometimes lacking. We have imposed a simple codification of size, substrate and methodology, so far as these could be ascertained.

Throughout the text, mention of species refers to entries in Table 1, unless otherwise indicated.

RESULTS AND DISCUSSION

Generalities

The data of Table 1 represent too great a variety of substrates, investigative techniques, and sampling intensities to allow valid comparisons among species. The largest values are probably near the maxima achievable under field conditions whereas many, perhaps most, of the smaller values certainly are not.

Table 1 supplements other summaries (Büsgen and Münch, 1929; Lyr and Hoffman, 1967; Armson, 1977; Hansen, 1981) demonstrating that some species extend roots rapidly in youth. Thus, the radial spread of *Tournefortia argentea* was 18 m at age 3 years after natural seeding, and that of *Pinus elliottii* was 9.8 at age 5 years after planting. The depth of *Pinus radiata* was over 2 m at 1 year after planting with intensive culture, and 2.6 m at age 4

TABLE I

Reported maximum rooting depths and radii of selected trees and shrubs (see end of table for abbreviations)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum Depth (m)	Maximum Radius (m)	Evidence	Reference
GYMNOSPERMS						
Araucariaceae						
Agathis australis Salisb.	Mature	sicl	> 3.6	–	O	F. Morrison (personal communication, 1962)
Cupressaceae						
Cupressaceae	15–25 m	c	–	20.0	R	Cutler and Richardson (1981)
Cupressus lusitanica Miller	8 years	l	4.9	–	C,W	Hosegood and Howland (1966)
Cupressus macrocarpa Hartw.	13–20 years	sl/sc	4.6	–	E,W	Pereira and Hosegood (1962)
Juniperus monosperma (Engelm.) Sarg.	–	r,wt	19.8	–	Tr	Cannon and Starrett (1956)
J. monosperma	–	mine,r	> 61.0	–	O	Cannon (1960)
J. monosperma	–	r	21.2	–	Tr	In Kleinhampl and Koteff (1960)
Juniperus procera Endl.	–	–	–	12.0(1)	E	Glover (1952)
Juniperus scopulorum Sarg.	25 years	c	–	7.0	E	Bunger and Thomson (1938)
Juniperus virginiana L. (W)	34 years	Loess	2.2	9.2	E	Sprackling and Read (1979)
J. virginiana (W)	Mature	cl,sl	> 7.6	6.1	E	Bunger and Thomson (1938)
J. virginiana	Mature	sil/c	–	10.1	Tr	Brown and Woods (1968)
Thuja plicata Donn.	> 30 years	sil	–	avg.10.0	E	Eis (1974)
T. plicata	63 years	s	–	10.0	E	Eis (1987)
T. plicata	9 m	Peat	–	6.4	E	Rigg and Harrar (1931)
Pinaceae						
Abies alba Mill.	30 years	Heavy	1.5	–	R	Röhrig (1966)
A. alba	Mature	l	1.5	–	R	Köstler et al. (1968)
Abies balsamea (L.) Mill.	< 180 years	Coarse	3.0	–	E	Schultz (1978)
Abies lasiocarpa (H.) Nutt.	180–200 years	–	1.5	14.0	E	T.W. Daniel (personal communication, 1979)
A. lasiocarpa	20–25 m	grsil/coarse	> 4.0	–	O	R.F. Fisher (personal communication, 1988)
Larix decidua Mill.	7–8 years	sl	3.3	–	R	White and Wood (19[illegible])

A. lasiocarpa	20–25 m	grsil/c	>4.0	–	O	R.F. Fisher (personal communication, 1988)

Larix decidua Mill.	7–8 years	sl	3.3	–	R	White and Wood (1958)
L. decidua	90 years	ls	2.5	–	R	Köstler et al. (1968)
L. decidua	–	Chalk, r	4.5	–		Köstler et al. (1968)
Larix laricina (DuRoi) K. Koch	–	s	1.2	>9.1	E	Bannan (1940)
Larix leptolepis (Sieb&Zucc.) Gord.	30 years	s/l	2.8	7.1	R	Köstler et al. (1968)
Larix sibirica Ledeb.	24 years	l	>1.6	–	E	Verzunov (1980)
Picea abies (L.) Karst.	4 years	sicl	3.7	–	W	Horner and McCall (1944)
P. abies	30 years	Various	2.1	9.3	E	Vater (1927)
P. abies	46–77 years	Moraine	–	7.9	E	Laitakari (1929)
P. abies	Mature	ls	6.0	18.0	R	Köstler et al. (1968)
P. abies	–	Moraine	–	7.5	E	Holstener-Jorgensen (1959)
Picea engelmannii Parry ex Engelm.	20–25 m	grsil/coarse	>4.0	–	O	R.F. Fisher (personal communication, 1988)
Picea glauca (Moench) Voss	<180 years	Various	3.0	–	E	Schultz (1978)
P. glauca	40–50 years	sl	–	20.0	E	Lyford (1972)
P. glauca	≈180 years	Loess	2.4	–	O	E.L. Stone (unpublished observations, 1974)
P. glauca	12 m	s	1.4	18.6	E	Bannan (1940)
Picea mariana (Mill) B.S.P.	–	Peat	–	9.1	O	Vincent (1965)
Picea sitchensis (Bong.) Carr.	100–200 years	–	–	13.0	E	T.W. Daniel (personal communication, 1979)
P. sitchensis	–	–	>2.1	–	O	Day (1963)
P. sitchensis	–	Peat	–	>23.0	O	Harris (1978)
Pinus banksiana Lamb.	32 years	cl	1.0	11.6	E	Yeager (1935)
P. banksiana	14 m	s	2.1	8.5	E	Cheyney (1932)
P. banksiana	18 m	–	2.0	14.0	E	Strong and LaRoi (1983)
P. banksiana	–	ls	>2.7	–	E	Adams and Chapman (1941)
P. banksiana	–	s	2.9	–	O	Gevorkiantz et al. (1943)
Pinus caribaea Morelet	16 years	s	>3.6	–	E	Haigh (1966)
Pinus clausa (Chapm.) Vasey	40–60 years	s	4.0	–	O	Kalisz and Stone (1984)
Pinus contorta Doug.	90 years	si/c	>1.0	6.4	E	Bishop (1962)
P. contorta	2.4 m	Peat	–	7.0	E	Rigg and Harrar (1931)
P. contorta	9–12 m	sl,sic	>2.0	–	O,W	Johnston (1975)
P. contorta	–	Various	>3.3	8.2	E	Horton (1958)
P. contorta	–	Coarse	–	7.0	E,O	Smith (1964)
Pinus echinata Mill.	30–40 years	ls/c	>1.7	–	W	Metz and Douglass (1959)

TABLE I (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum		Evidence	Reference
			Depth (m)	Radius (m)		
P. echinata	100 years	s	> 3.3	–	W	Lull and Axley (1958)
Pinus edulis Engelm.	–	r	19.8	–	Tr	Cannon and Starrett (1956)
P. edulis	–	r	21.2	–	Tr	Kleinhampl and Koteff (1960)
Pinus elliottii Engelm.	5 years	s	–	9.8	Tr	Pritchett and Robertson (1960)
P. elliottii	5 years	s	–	7.0	E	White and Pritchett (1970)
P. elliottii	11–12 years	s,wt	3.0	–	E	Schultz (1972)
P. elliottii	15 years	–	4.6	–	E	Haigh (1966)
P. elliottii	25 years	s	–	> 18.0	E	Pritchett and Lyford (1978)
P. elliottii	20 years	s/sl	4.0	–	C	E.L. Stone and P.J. Kalisz (unpublished observations, 1982)
Pinus flexilis James.	15 m	sil,cave,r	10.0	–	O	R.F. Fisher (personal communication, 1988)
Pinus halepensis Mill.	–	chalk,r	4.5	–	W	Sanchori et al. (1967)
P. halepensis	–	s,r	4.0	–	E	Oppenheimer (1945)
Pinus lambertiana Dougl.	85 years	sic/sicl	5.5	12.2	W	Ziemer (1978)
Pinus laricio Poiret	22 years	s	> 1.2	> 7.0	W	Lunt (1934)
Pinus monticola Dougl.	11 m	Till	–	7.0	E	Rigg and Harrar (1931)
P. monticola	18 m	Peat	–	14.2	E	Rigg and Harrar (1931)
Pinus palustris Mill.	30–33 years	l/sl	–	14.3	E	Hodgkins and Nichols (1977)
P. palustris	90 years	s/scl	> 5.0	–	E	E.L. Stone (unpublished observations, 1981)
P. palustris	Mature	s	4.6	15.5	E	Heyward (1933)
P. palustris	Mature	s	> 4.3	22.2	R	Wahlenberg (1946)
P. palustris	Mature	s/ls	–	16.8	Tr	Hough et al. (1965)
P. palustris	–	s/c	> 2.7	–	E	Oliver (1978)
Pinus patula Schl. & Cham.	8 years	l	4.9	–	C,W	Hosegood and Howland (1966)
P. patula	–	l	> 6.0	–	W	Russell (1973)
Pinus pinaster Ait.	3 years	s	> 3.0	6.4	E	Burbidge (1936)
P. pinaster	18 years	s	7.0	–	W	Butcher and Havel (1976)
Pinus ponderosa Laws. (W)	47 years	l,sl/gr	–	25.6	E	Greb and Black (1961)
P. ponderosa	50–60 years	s,sl	1.1	9.1	E	Hermann and Peterson (1969)
P. ponderosa	60 years	grsl,r	> 1.3	16.2	E	Curtis (1964)
P. ponderosa	63 years	l,cl,r	1.7	6.1	E	Berndt and Gibbons (1958)

P. ponderosa	63 years	l,cl,r	1.7	6.1	E	Berndt and Gibbons (1958)
P. ponderosa	–	r	12.2	–	O	In Lutz and Chandler (1946)
P. ponderosa	–	r	24.0	–	R	Cannon (1960)
Pinus radiata D. Don	1 year	s	> 2.0	–	W	Nambiar (1983)
P. radiata	4 years	s	1.8	–	E	Parker (1987)
P. radiata	> 10 years	Coarse	2.4	–	O	Pryor (1937)
P. radiata	16 years	Red earth	4.5	–	W	Greenwood et al. (1981)
P. radiata	18 years	s	> 3.7	–	E	Will (1966)
P. radiata	22 years	s	4.0	–	W	Jackson et al. (1983)
P. radiata	26–36 years	sl/sc	4.6	–	E,W	Pereira and Hosegood (1962)
P. radiata	39 years	s	8.0	–	C	Parker (1987)
Pinus resinosa Ait.	12 years	s	1.9	5.5	E	Day (1941)
P. resinosa	13 years	s	–	9.8	E	Stiell (1970)
P. resinosa	≈ 25 years	s	2.1	–	W	Urie (1959)
P. resinosa	25 years	s	2.7	–	E	White and Wood (1958)
P. resinosa	32 years	s	2.8	10.0	E	Fayle and Pierpont (1975)
P. resinosa	39 years	ls	2.7	9.0	E	Leaf et al. (1971)
P. resinosa	70–100 years	Various	3.7	10.7	E	Brown and Lacate (1961)
P. resinosa	Mature	s	> 3.0	–	O	Armson and Williams (1960)
P. resinosa	–	ls	> 2.1	–	W,O	Bay and Boelter (1963)
P. resinosa	–	ls	> 2.4	–	P	Adams and Chapman (1941)
P. resinosa	–	s	> 2.4	–	E	DeMent and Stone (1968)
Pinus rigida Mill.	Mature	s	–	10.7	E	McQuilkin (1935)
P. rigida	7 m	s	2.7	–	E	McQuilkin (1935)
Pinus serotina Michx.	–	cl/s,wt	> 2.0	–	O	E.L. Stone (unpublished observations, 1970)
Pinus strobus L.	23 years	s,wt	3.3	–	E	E.L. Stone (unpublished observations, 1951)
P. strobus	25 years	sl	–	21.3	–	Palmer (1960)
P. strobus	64–90 years	Various	3.0	12.2	E	Brown and Lacate (1961)
P. strobus	Mature	s	4.0	–	R	Köstler et al. (1968)
Pinus sylvestris L.	> 14 years	Various	> 4.8	8.7	E,O	Vater (1927)
P. sylvestris	> 14 years	r	6.8	–	O	Vater (1927)
P. sylvestris	45 years	s/till,r	> 2.7	–	P	Roberts (1976)
P. sylvestris	135–149 years	s,wt	3.2	21.0	E	Laitakari (1929)
P. sylvestris	250 years	s	2.4	–	–	Aaltonen (1920)
P. sylvestris	8–26 m	–	2.0	–	P	Tolle (1967)
P. sylvestris	–	Various	8.0	–	R	Röhrig (1966)
P. sylvestris	–	s,wt	5.0	–	O	Orlov (1980)

TABLE 1 (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum Depth (m)	Maximum Radius (m)	Evidence	Reference
Pinus taedea L.	11 years	ls/c	2.4	–	W,C	Hoover et al. (1953)
P. taeda	21 years	sl/cl	6.1	–	W,O	Patric et al. (1965)
Pseudotsuga menziesii (Mirb.) Franco	4 years	sicl	3.7	–	W	Horner and McCall (1944)
P. menziesii	> 30 years	sil	–	av.12.0	E	Eis (1974)
P. menziesii	34 years	s	–	13.0	E	Eis (1987)
P. menziesii	70 years	–	> 3.2	–	R	Köstler et al. (1968)
P. menziesii	72 years	l/cl	1.5	6.4	E	Berndt and Gibbons (1958)
P. menziesii	495 years	l	3.0	–	E	Santantonio et al. (1977)
P. menziesii	Mature	Cave,r	≈ 10.0	–	O	J.K. Agee (personal communication, 1990)
Tsuga heterophylla (Raf.) Sarg.	> 30 years	sil	–	av.10.0	E	Eis (1974)
T. heterophylla	38 years	s	> 1.9	10.0	E	Eis (1987)
T. heterophylla	6 m	Peat	–	10.0	E	Rigg and Harrar (1931)
Podocarpaceae						
Podocarpus spicatus R.Br.	15 m	–	–	> 19.5	E	Allan (1926)
Taxodiaceae						
Sequoia sempervirens (D.Don) Endl.	1000 years	Alluvium	5.0[a]	–	E	Zinke (1977)
Sequoiadendron giganteum (Lindl.) Buchh.	366 cm	–	–	38.1	E	Hartsveldt et al. (1975)
Mixed stands						
Picea engelmanii and *Abies lasiocarpa*	–	c,cl,l	> 2.1	–	E,O	Brown and Thompson (1965)
Pinus ponderosa and *P. lambertiana*	–	s,r	> 2.7	–	W	Arkley (1981)
Pinus taeda and *P. echinata*	17–20 years	sil	> 1.5	–	W	Zahner (1955)

ANGIOSPERMS						
Aceraceae						
Acer L. sp.	24 m	c	–	20.0	O	Cutler and Richardson (1981)
Acer negundo L.	5–15 years	sil,c	4.0	3.7	E	Biswell (1935)
A. negundo (W)	34 years	sil	3.3	3.6	E	Sprackling and Read (1979)
A. negundo	40 years	c	1.3	14.0	E	Yeager (1935)
Acer pseudoplatanus L.	Mature	sl	1.4	9.0	R	Köstler et al. (1968)
Acer rubrum L.	55 years	Till	> 1.2	8.5	E	Stout (1956)
A. rubrum	60 years	Till	–	17.5	E	Lyford and Wilson (1964)
A. rubrum	65 years	s	3.0	–	E,C	Haag et al. (1989)
A. rubrum	–	sl	–	20.0	E	Wilson and Horsley (1970)
Acer saccharinum L. (W)	31 years	sil	3.3	6.4	E	Sprackling and Read (1979)
A. saccharinum	35 years	c	1.3	14.9	E	Yeager (1935)
Acer saccharum Marsh.	61–104 years	Till	–	13.7	E	Stout (1956)
A. saccharum	85 years	s	1.8	–	E	Fayle (1965)
A. saccharum	Mature	sl	2.7	–	W	Schneider et al. (1966)
Anacardiaceae						
Mangifera indica L. (H)	–	sil	5.5	–	E	Howard (1925)
Rhus viminalis Vahl.	–	Alluvium	> 25.0	–	O	Cannon (1924)
Annonaceae						
Annona L. sp. (H)	–	sil	4.3	–	E	Howard (1925)
Apocynaceae						
Acokanthera nabaio Schweinf.	–	–	–	12.0(1)	E	Glover (1952)
Balanitaceae						
Balanites orbicularis Sprauge	–	–	–	15.0(1)	E	Glover (1952)
Betulaceae						
Alnus formosana (Burkill) Makino	21 years	sil,sic,r	1.7	–	E	Yen et al. (1978)
Alnus glutinosa (L.) Gaertn.	75 years	–	3.8	–	R	Köstler et al. (1968)
Betula L. sp.	12–14 m	c	–	10.0	R	Cutler and Richardson (1981)
Betula sp.	20–60 years	–	> 3.6	–	R	Röhrig (1966)
Betula lutea Michx. f.	50 years	s	> 1.5	–	E	Fayle (1965)
Betula odorata Bechst.	33–84 years	Various	2.7	9.6	E	Laitakari (1934)
Betula papyrifera Marsh.	25 years	–	–	> 8.0	E	Pulling (1918)

TABLE 1 (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum		Evidence	Reference
			Depth (m)	Radius (m)		
B. papyrifera	–	–	> 1.3	–	E	Pomerleau and Lortie (1962)
B. papyrifera	–	sl	–	20.0	E	Wilson and Horsley (1970)
Betula verrucosa Ehrh.	33 years	s	4.0	–	R	Köstler et al. (1968)
B. verrucosa	45–150 years	s	1.1	23.8	E	Laitakari (1934)
Carpinus betulus L.	70–80 years	c	1.4	–	R	Köstler et al. (1968)
Bignoniaceae						
Catalpa speciosa Warder (W)	30 years	sl	3.0	2.3	E	Sprackling and Read (1979)
Jacaranda decurrens Cham.	–	–	> 10.0	–	R	Chaney (1981)
Millingtonia hortensis L.f. (H)	–	–	3.5	–	E	Howard (1925)
Tabebuia aurea (Manso) Benth. & Hook. ex. S. Moore	27 cm(ds)	s,wt	> 1.4	–	E	B. Dubs (unpublished work, 1990)
Tabebuia impetigosa Mort. ex DC.	52 cm(ds)	s,wt	> 1.4	–	E	B. Dubs (unpublished work, 1990)
Bombaceae						
Adansonia digitata L.	Mature	–	–	46.0	R	Fenner (1980)
Boraginaceae						
Cordia glabrata A.DC.	25 cm(dc)	s,wt	> 1.4	–	E	B. Dubs (unpublished work, 1990)
Cordia subcordata Lam.	5 years	s	> 3.1	–	E	E.L. Stone (unpublished observations, 1990)
C. subcordata	< 16 years	s,wt	2.6	–	E	E.L. Stone (unpublished observations, 1986)
Tournefortia argentea Linn.f.	3 years	s	–	18.0	E	Billings (1964)
Casuarinaceae						
Casuarina cristata Miq.	–	sl/c	> 2.5	–	E	Shea et al. (1978)
Casuarina equisetifolia J.R. & G. Forst.	10 years	s,wt	4.0	–	E	Kaupenjohann and Zech (1988)
C. equisetifolia	Stunted	Dunes	4.5	–	E	Yadav (1981)
Casuarina pusilla Macklin	–	s/c	> 2.4	–	E	Specht and Rayson (1957)

G. Forst.	Stunted	Dunes	4.5	–	E	Yadav (1981)
C. equisetifolia						
Casuarina pusilla Macklin	–	s/c	> 2.4	–	E	Specht and Rayson (1957)
Chenopodiaceae						
Saracobatus vermiculatus (Hook.) Torr.	–	Mine,r	17.3	–	O	Meinzer (1927)
Compositae						
Artemesia tridentata Nutt.	–	–	9.1	–	O	Woodbury (1947)
Cornaceae						
Cornus florida L.	Mature	sil/c	–	9.7	Tr	Brown and Woods (1968)
Dillenaceae						
Curatella americana L.	–	Wet	–	18.0	R	Doley (1981)
C. americana	–	–	6.0	–	–	Foldats and Rutkis (1975)
Dipterocarpaceae						
Shorea negrosensis Foxw.	Mature	Ash	> 4.0	–	O	E.L. Stone (unpublished observations, 1959)
Ericaceae						
Oxydendrum arboreum (L.)DC	–	sil/c	–	12.6	Tr	Brown and Woods (1968)
Euphorbiaceae						
Aleurites fordii Hensl. (H)	6 years	s	2.4	–	E	Dunscombe (1931)
Hevea brasiliensis (Willd. ex A. Juss.) Müll. Agr. (H)	> 10 years	–	–	> 24.0	T E	Haines et al. (1954)
Phyllanthus emblica L.	–	s,wt	5.8	–	E	Howard (1925)
Sapium discolor Müll. Arg.	15 years	sil,sic	1.7	–		Yen et al. (1978)
Fabaceae						
Acacia aneura F. Muell.	Mature	–	> 1.2	14.0	C	Pressland (1975)
Acacia bussei Harms	4 m	–	–	14(1)	E	Glover (1952)
Acacia ethaica Schweinf.	–	–	–	15	O	Glover (1952)
Acacia koa A. Gray	–	–	–	30.5	O	Baldwin and Fagerlund (1943)
Acacia mellifera Benth.	4 m	–	–	15.0	E	Adams (1966)
A. mellifera	–	–	–	15.0	E	Glover (1952)
Acacia mearnsii DeWild. (H)	8 years	l	> 5.5	–	E	Hosegood (1963)
Acacia raddiana Savi.	300 years	wt	35.0	–	O	Anon. (1974)
A. raddiana	–	wt	> 5.0	–	E	Boyko (1954)
Acacia seyal Del.	7 m	c	1.2	8.0	E	Adams (1966)
Acacia tortilis (Forsk.) Hayne	3 m	–	> 1.3	14.5	E	J. Belsky (personal communication, 1989)
Acacia spirocarpa Hochst.	27 cm	–	–	> 10.6(1)	E	Glover (1952)

TABLE 1 (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum Depth (m)	Maximum Radius (m)	Evidence	Reference
A. spirocarpa	–	wt	> 5.0	–	E	Boyko (1954)
Albizia gummifera C.A. Smith [= *A. adianthifolia* (Schumach.) W.F. Wright]	15 m	–	> 6.1	9.1	E	Kerfoot (1962)
Andira humilis Mart.	–	wt	18.0	–	E	Rawitscher (1948)
Butea frondosa Roxb. (H)	–	s	5.2	–	E	Howard (1925)
Caragana arborescens Lam. (W)	23 years	l,sl/coarse	–	10.9	E	Greb and Black (1961)
Clathotropis brachypetala Kleinh.	–	sl/c	3.5	10.0	E	Förster (1970)
Dalbergia sisso Roxb. ex DC.	–	s	4.5	–	E	Howard (1925)
Dipteryx alata Vog.	37 cm (ds)	s,wt	> 1.5	–	E	B. Dubs (unpublished work, 1990)
Dipteryx panamensis (Pittier) Record	30 m	cl	5.0	–	O	R.F. Fisher (personal communication, 1988)
Gleditsia triancanthos L.	4–6 years	c	1.6	5.2	E	Biswell (1935)
G. triacanthos (W)	Mature	cl,sl	3.3	–	E	Bunger and Thomson (1938)
G. triacanthos	12 m	c	–	15.0	R	Cutler and Richardson (1981)
G. triacanthos (W)	28 years	sicl	3.0	5.0	E	Sprackling and Read (1979)
Leptadenia pyrotechnica (Forsk.) Decne.	2 m	s/si/c	11.5	5.0	E	Betanowny and Wahab (1973)
Prosopis cineratia (L.) Druce	–	–	–	27.0	O	Evenari (1938)
Prosopis farcta (Soland.) Macbride	–	wt	15.0	–	–	Schmueli (1948)
Prosopis glandulosa Torr.	5 m	cl,wt	6.0	–	W,C	Nilsen et al. (1983)
P. glandulosa	Large	cl	13.0	–	C	Jenkins et al. (1988)
Prosopis 'juliflora' (Swartz) DC. (= *P. glandulosa*?)	6 m	sl,c	3.0	19.0	W	Cable (1977)
P. 'juliflora' (= *P. velutina*)	–	Coarse	> 53.0	–	O	Phillips (1963)
Prosopis tamarugo Phil.	–	–	> 3.5	–	C	Mooney et al. (1980)

Prosopis velutina Woot.

P. glandulosa	Large	cl	13.0	–	C	Jenkins et al. ([illegible])
Prosopis 'juliflora' (Swartz) DC. (= *P. glandulosa*?)	6 m	sl,c	3.0	19.0	W	Cable (1977)
P. 'juliflora' (= *P. velutina*)	–	Coarse	> 53.0	–	O	Phillips (1963)
Prosopis tamarugo Phil.	–	–	3.5	–	C	Mooney et al. (1980)

Prosopis velutina Woot.	–	Alluvium	8.0	15.0	R	In Cannon (1911)
P. velutina	–	wt	≈ 14.0	–	O	Minckley and Brown (1982)
Robinia pseudoacacia L.	1 year	–	2.1	–	R	Lyr and Hoffmann (1967)
R. pseudoacacia	4 years	si,cl	3.7	–	W	Horner and McCall (1944)
R. pseudoacacia (W)	12 years	si,cl	2.4	2.7	E	Sprackling and Read (1979)
R. pseudoacacia	28–70 years	s	2.8	14.0	R	Köstler et al. (1968)
R. pseudoacacia (W)	Mature	cl,sl	> 7.9	6.4	E	Bunger and Thomson (1938)
R. pseudoacacia	18–20 m	c	–	12.4	R	Cutler and Richardson (1981)
Fagaceae						
Fagus L. sp.	20 m	c	–	15.0	R	Cutler and Richardson (1981)
Fagus grandifolia Ehrh.	53 years	Till	> 1.5	4.3	E	Stout (1956)
F. grandifolia	130 years	sl	> 2.3	–	O	E.L. Stone (unpublished observations, 1990)
Fagus sylvatica L.	Mature	Various	1.8	6.2	–	Vater (1927)
Nothofagus fusca (Hook. f.) Zrst.	Mature	sil/pumice	> 2.0	–	O	E.L. Stone (unpublished observations, 1962)
Quercus L. sp.	16–23 m	c	–	30.0	R	Cutler and Richardson (1981)
Quercus sp.	–	c,s	–	8.5	E	Holstener-Jorgensen (1959)
Quercus sp.	–	–	5.0	–	O	Cermak et al. (1980)
Quercus spp. (*erythrobalanus*)	Mature	sil,c	–	12.7	Tr	Brown and Woods (1968)
Quercus spp. (*leucobalanus*)	Mature	sil,c	–	11.7	Tr	Brown and Woods (1968)
Quercus agrifolia Nee	–	–	7.3	–	O	Kummerow (1981)
Q. agrifolia (or *Q. lobata* Nee)	Mature	–	9.1	27.4	E	Thomas (1980)
Quercus alba L.	40 years	Till	1.1	6.7	E	Stout (1956)
Q. alba	50 years	sil/c	3.4	–	Tr	Kalisz et al. (1988)
Q. alba	65 years	sil	4.0	–	E	Hammer (1986)
Quercus chrysolepis Liebm.	–	r	7.3	–	O	Hellmers et al. (1955)
Quercus coccinea Muenchh.	Mature	scl/sl	7.0	–	C	Patric (1988)
Quercus douglasii Hock & Arn.	–	r,wt	24.2	–	Tr	Lewis and Burgy (1964)
Quercus dumosa Nutt.	1.5 m	r	8.5	–	O	Hellmers et al. (1955)
Quercus gambellii Nutt.	2–4 m	Coarse	> 2.4	–	W	Tew (1966)
Quercus laevis Walt.	Mature	s	–	14.8	Tr	Hough et al. (1965)
Quercus lobata Nee	–	–	–	21.3	E	Cannon (1914)
Quercus macrocarpa Michx.	1 year	–	1.9	–	R	Lyr and Hoffmann (1967)
Q. macrocarpa	27 years	ls,s	> 3.3	–	E	Crossley (1940)
Q. macrocarpa	43 years	c	2.5	12.4	E	Yeager (1935)
Q. macrocarpa	50–65 years	sil	4.6	18.3	E	Weaver and Kramer (1932)

TABLE 1 (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum Depth (m)	Maximum Radius (m)	Evidence	Reference
Q. macrocarpa (W)	80 years	Loess	4.8	12.1	E	Sprackling and Read (1979)
Q. macrocarpa	3.6 m	c	4.4	3.3	E	Biswell (1935)
Quercus michauxii Nutt.	Mature	s/cl	>2.0	–	O	E.L. Stone (unpublished observations, 1981)
Quercus prinus L.	36 years	s	–	5.8	E	Wood (1939)
Q. prinus	63–82 years	Till	1.1	7.3	E	Stout (1956)
Q. prinus	–	r	>2.4	–	O	J.H. Patric (personal communication, 1988)
Quercus robur L.	11–13 years	–	9.0	–	R	Köstler et al. (1968)
Q. robur	30 years	s	–	18.0	R	Röhrig (1966)
Quercus rubra L.	17–84 years	Till	–	7.0	E	Stout (1956)
Q. rubra	60 years	Favorable	2.9	–	R	Röhrig (1966)
Q. rubra	65 years	s,l	3.6	–	R	Köstler et al. (1968)
Q. rubra	Mature	sl	1.0	15.0	E	Lyford (1980b)
Q. rubra	44 cm	s	1.2	>12.5	W	Lunt (1934)
Quercus suber L.	–	s/c	–	23.0	E	Métro and Sauvage (1959)
Quercus turbinella Greene	2.4 m	sl,r	6.4	–	E	Davis and Pase (1977)
Q. turbinella	Shrub	r	>9.0	–	O	Saunier and Wagle (1967)
Quercus virginiana Mill.	Old	–	–	30.5	O	T.O. Perry (personal communication, 1984)
Quercus wislizenii A.DC.	–	r,wt	24.2	–	Tr	Lewis and Burgy (1964)
Hammamelidaceae						
Liquidambar styraciflua L.	40 years	–	–	>6.9	E	Kormanik and Brown (1967)
Hippocastanaceae						
Aesculus L. sp.	25 m	c	–	23.0	R	Cutler and Richardson (1981)
Icaninaceae						
Apodytes dimidiata E. Mey. ex Arn.	Mature	r	8.2	10.7	E	Kerfoot (1963)
Juglandaceae						
Carya Nutt. sp.	20 years	sil	>1.8	–	E,O	Gaiser (1952)
Carya sp.	Mature	sil,c				

Aesculus L. sp.	25 m	c	–	25.0	K	Cutler and Richardson (1981)
Icaninaceae						
Apodytes dimidiata E. Mey. ex Arn.	Mature	r	8.2	10.7	E	Kerfoot (1963)
Juglandaceae						
Carya Nutt. sp.	20 years	sil	> 1.8	–	E,O	Gaiser (1952)
Carya sp.	Mature	sil,c	–	16.6	Tr	Brown and Woods (1968)
Carya cordiformis (Wangenh.) K. Koch (W)	28 years	sil	3.0	1.8	E	Sprackling and Read (1979)
Carya illinoinensis (Wangenh.) K. Koch (H)	> 3 years	Coarse	> 3.0	9.1	E	Woodroff and Woodroff (1934)
C. illinoinensis (H)	40 years	sl	–	> 10.0	Tr	Hammer et al. (1953)
Carya ovata (Mill.) K. Koch (W)	40 years	sil	2.1	6.1	E	Sprackling and Read (1979)
Juglans microcarpa Berland. (W)	Mature	cl,sl	1.8	15.8	E	Bunger and Thomson (1938)
Juglans nigra L.	7–12 years	c	1.8	6.1	E	Biswell (1935)
J. nigra (W)	15 years	sicl	3.3	4.5	E	Sprackling and Read (1979)
J. nigra	25 years	c	1.6	16.5	E	Yeager (1935)
J. nigra	30 years	Prairie	2.2	–	E	Pham et al. (1978)
J. nigra	30–35 years	–	2.2	–	E	Yen et al. (1978)
J. nigra (W)	49 years	l,sl/gr	–	34.1	E	Greb and Black (1961)
Juglans regia L. (H)	13 years	l	> 3.6	–	W	Viehmeyer and Hendrickson (1938)
J. regia (H)	24 years	s/si	2.2	16.0	E	Tamási (1986)
Lecythidaceae						
Cariniana pyriformis Miers	–	sl,c	2.0	25.0	E	Förster (1970)
Loranthaceae						
Nuytsia floribunda (Labill.) R.Br.	4 m	s	> 1.4	> 50.0	E	Hocking (1980)
Magnoliaceae						
Liriodendron tulipifera L.	84 years	Coarse/fine, r	> 2.9	–	O	Hammer (1986)
L. tulipifera	130 years	sl	> 2.2	–	O	E.L. Stone (unpublished observations, 1990)
Magnolia grandifolia L.	Mature	s,cl	> 2.0	–	O	E.L. Stone (unpublished observations, 1981)
Meliaceae						
Melia azedarach L.	–	s	3.9	–	O	Howard (1925)
Moraceae						
Artocarpus altilis (Parkins.) Fob.	Mature	s	–	> 18.3 (15 mm)	E	M. Stuart (personal communications, 1990)
Chlorophora excelsa Benth. & Hook.P.	–	–	–	7.0	–	Mensah and Jeník (1968)

TABLE 1 (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum Depth (m)	Maximum Radius (m)	Evidence	Reference
Ficus benghalensis L.	–	s	4.8	–	E	Howard (1925)
Ficus religiosa L.	–	s	5.9	–	E	Howard (1925)
Maclura pomifera (Raf.) Schneid. (W)	23 years	sicl	2.4	4.5	E	Sprackling and Read (1979)
M. pomifera (W)	Mature	cl,sl	8.2	4.3	E	Bunger and Thomson (1938)
M. pomifera (W)	10 m	cl	–	> 19.3 (5 mm)	E	L. Fox (personal communication, 1989)
Morus alba L. (W)	Mature	cl,sl	–	12.7	E	Bunger and Thomson (1938)
Myrtaceae						
Eucalyptus sp.	Mature	Cave,r	60.0	–	O	Jennings (1971)
Eucalyptus baxteri (Benth.) Maiden & Blakely ex J.M. Black	–	Cave,r	> 20.0	–	O	D.H. Ashton (personal communication, 1981)
Eucalyptus calophylla R. Br. ex Lindl.	–	Cave,r	45.0	–	O	Campion (1926)
Eucalyptus camaldulensis Dehn. (W)	31 years	–	> 2.0	20.0	P	Zohar (1985)
E. camaldulensis	–	–	9.0	–	O	Day (1959)
Eucalyptus citriodora Hook.	6 years	s,wt	1.5	–	E	Haigh (1966)
Eucalyptus clelandi (Maiden) Maiden	–	sl,c	> 2.5	> 6.0	E	Shea et al. (1978)
Eucalyptus diversicolor F.J. Muell.	–	Cave,r	> 18.0	–	O	Campion (1926)
Eucalyptus globulus Labill.	10 years	s	4.2	> 5.8	E	Giordano (1969)
Eucalyptus gomphocephala DC.	–	–	9.0	–	O	Day (1959)
E. gomphocephala	–	Cave,r	15.0	–	O	Lamont and Lange (1976)
Eucalyptus grandis W. Hill ex Maiden	2–3 years	Podzolic	5.6	–	W	In Nambiar (1990)
E. grandis	5 years	s	1.8	–	E	Haigh (1966)

E. gomphocephala	–	Cave,r	15.0	–	O	Lamont and Lange (1976)
Eucalyptus grandis W. Hill ex Maiden	2–3 years	Podzoli	5.6	–	W	In Nambiar (1990)
E. grandis	5 years	s	1.8	–	E	Haigh (1966)
Eucalyptus leucoxylon F.J. Muell.	–	–	–	> 16.0	O	Cannon (1921)
Eucalyptus marginata Sm.	Pole-size	s/c,wt	15.0	–	–	Kimber (1974)
E. marginata	Mature	s/c,wt	19.0	–	C	Carbon et al. (1980)
E. marginata	–	c	40.0	–	C	Dell et al. (1983)
Eucalyptus pilularis Sm.	–	Podzol	10.0	–	O	Thompson and Hubble (1980)
Eucalyptus regnans F.J. Muell.	235 years	r	7.1	13.6	O,E	Ashton (1975)
Eucalyptus saligna Sm.	–	l	4.9	–	W,C	Hosegood and Howland (1966)
E. saligna	–	cl	> 6.0	–	W	Russell (1973)
Eucalyptus trivalva Blakely	–	sl,c	> 2.0	> 15.0	E	Shea et al. (1978)
Eucalyptus viminalis Labill.	–	Cave,r	17.7	–	O	Johnson et al. (1968)
Melaleuca L. sp.	–	sl/c	> 2.5	–	–	Shea et al. (1978)
Metrosideros collina [= *M. collinus* (J.R. Forst.) A.Gray]	–	–	5.0	> 30.0	O	Berger et al. (1981)
Psidium guajava L. (H)	–	sil	4.9	–	E	Howard (1925)
Oleaceae						
Fraxinus L. sp. (W)	Mature	cl,sl	1.8	13.1	E	Bunger and Thomson (1938)
Fraxinus sp.	14–23 m	c	–	21.0	R	Cutler and Richardson (1981)
Fraxinus americana L. (W)	18 years	sil	1.8	7.3	E	Sprackling and Read (1979)
F. americana	71 years	Till	–	10.4	E	Stout (1956)
Fraxinus angustifolia Vahl.	20 years	Alluvium, wt	2.2	–	E	Šika (1963)
Fraxinus anomola Torr. ex Wats.	–	–	3.0	–	R	Cannon (1960)
Fraxinus pennsylvanica Marsh.	43 years	c	1.1	14.6	E	Yeager (1935)
F. pennsylvanica (W)	45 years	ls	2.7	7.0	E	Sprackling and Read (1979)
Fraxinus velutina Torr.	–	–	6.1	–	O	Robinson (1958)
Platanaceae						
Platanus L. sp.	25–30 m	c	–	15.0	R	Cutler and Richardson (1981)
Platanus occidentalis L.	5 years	l/c	2.1	2.7	E	Biswell (1935)
Proteaceae						
Banksia marginata Cav.	–	s,c	> 2.4	–	E	Specht and Rayson (1957)
Banksia ornata F.J. Muell. ex Meissn.	–	s,c	> 2.4	5.2	E	Specht and Rayson (1957)

TABLE 1 (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum		Evidence	Reference
			Depth (m)	Radius (m)		
Rosaceae						
Adenostoma fasciculatum H.&A.	1.5 m	r	7.6	3.7	O	Hellmers et al. (1955)
Amelanchier alnifolia Nutt.	30 cm[b]	Coarse,r	1.8	–	E	Woolley (1936)
Amelanchier utahensis Koehne	–	–	6.4	–	O	Cannon (1960)
Eriobotrya japonica (Thunb.) Lindl.–loquot (H)	–	sil	2.7	–	E	Howard (1925)
Malus Mill.–apple (H)	6–17 years	Loess	10.0	7.0	E	Yocum (1935)
Malus–apple (H)	7 years	cl,sc	> 2.7	> 3.6	E	Goff (1897)
Malus–apple (H)	10–11 years	l,s	3.0	5.4	E	Rogers and Vyvyan (1934)
Malus–apple (H)	16 years	–	–	7.4	E	Peren (1923)
Malus–apple (H)	16 years	c	3.1	7.9	E	Yeager (1935)
Malus–apple (H)	17 years	Loess	10.7	> 10.0	W	Wiggans (1935)
Malus–apple (H)	30 years	cl,sicl	> 3.8	–	P	Radyuk (1964)
Malus–apple	8–12 m	c	–	10.0	R	Cutler and Richardson (1981)
Prunus L. sp.	12 m	c	–	11.0	R	Cutler and Richardson (1981)
Prunus dulcis (Mill.) D.A. Webb (H)	10–50 years	l	3.7	–	W	Hendrickson and Veihmeyer (1955)
Prunus armeniaca L. (W)	Mature	cl,sl	2.4	9.0	E	Bunger and Thomson (1938)
P. armeniaca (H)	–	sl,cl	4.9	–	O	Proebsting (1943)
Prunus avium (L.) L. (H)	20 years	l	1.9	–	E	Oskamp (1932)
Prunus–cherry (H)	15 years	–	–	9.1	E	Peren (1923)
Prunus persica (L.) Batsch. (H)	3 years	s	3.8	3.8	C	Lyons (1962)
P. persica (H)	Mature	l	2.3	–	E	Oskamp (1932)
P. persica (H)	–	sc,c	3.0	4.6	E	Ballantyne (1916)
P. persica (H)	–	sil	4.7	–	E	Howard (1925)
Prunus–plum (H)	–	sil	4.9	–	E	Howard (1925)
Prunus domestica L. (H)	–	l	2.1	–	E	Oskamp (1932)
Pyrus communis L. (H)	8 years	s	3.4	2.0	E	Rogers (1933)
P. communis (H)	Mature	c,r	> 1.8	> 4.3	P	Aldrich (1935)
P. communis (H)	3.3 m	sc,c	2.7	3.0	E	Ballantyne (1916)

Rubiaceae

P. persica (H)	–	sil	[illegible]	–	[illegible]	[illegible]
Prunus–plum (H)	–	sil	4.9	–	E	Howard (1925)
Prunus domestica L. (H)	–	l	2.1	–	E	Oskamp (1932)
Pyrus communis L. (H)	8 years	s	3.4	2.0	E	Rogers (1933)
P. communis (H)	Mature	c,r	> 1.8	> 4.3	P	Aldrich (1935)
P. communis (H)	3.3 m	sc,c	2.7	3.0	E	Ballantyne (1916)
Rubiaceae						
Coffea arabica L. (H)	2–6 years	sl,cl,r	4.0	2.7	E	Nutman (1933)
C. arabica (H)	–	l	> 3.0	–	W	Pereira (1957)
Rutaceae						
Citrus L. sp. (H)	4 years	–	2.5	3.5	E	Aliyappa et al. (1968)
Citrus aurantium L. (H)	15 years	s	> 5.2	–	C	Ford (1954)
Citrus limon (L.) Burm. f. (H)	18 years	s	> 5.2	7.9	C	Ford (1954)
Salicaceae						
Populus L. sp.	28 m	c	–	30.0	R	Cutler and Richardson (1981)
Populus deltoides Marsh.	8 years	c	1.2	7.0	E	Francis (1985)
P. deltoides (W)	16 years	sicl	3.6	1.8	E	Sprackling and Read (1979)
P. deltoides	43 years	c	3.0	22.7	E	Yeager (1935)
Populus sargentii Dode.	3–7 years	l/c,c	2.6	1.5	E	Biswell (1935)
Populus tremula L.	40–60 years	c	1.5	–	R	Köstler et al. (1968)
Populus tremuloides Michx.	18 years	s	2.3	14.3	E	Day (1944)
P. tremuloides	20 years	–	–	29.0	E	Buell and Buell (1959)
P. tremuloides	28–46 years	–	> 3.0	–	O,W	Johnston (1970)
P. tremuloides	70–90 years	l,l/cl	1.5	14.6	E	Berndt and Gibbons (1958)
P. tremuloides	–	l	> 3.0	–	E	Gifford (1966)
P. tremuloides	–	–	–	30.5	O	Jones (1985)
P. tremuloides	–	–	> 1.8	–	W	Tew (1967)
Salix L. sp.	15–25 m	c	–	40.0	R	Cutler and Richardson (1981)
Salix sp.	–	–	> 3.6	–	R	Cannon (1960)
Salix amygdaloides Anderss.	4–16 years	sl,sil	4.2	6.7	E	Sprackling and Read (1979)
Salvadoraceae						
Dobera glabra A. DC.	2.7 m	lava/s	12.0	–	O	Glover (1952)
Sapindaceae						
Litchi chinensis Sonn. (H)	–	sil	3.8	–	E	Howard (1925)
Sterculiaceae						
Theobroma cacao L. (H)	30 years	sic,s	> 2.1	> 6.1	E	McCreary et al. (1943)
Tamaricaceae						
Tamarix pentatandra Pallas	10 years	–	2.0	–	E	Yeager (1935)
T. pentatandra	5 m	sl/c,wt	3.7	3.3	E	Gary (1963)

TABLE 1 (continued)

Species	Age (years) or height (m) or DBH (cm)	Substrate (m)	Maximum		Evidence	Reference
			Depth (m)	Radius (m)		
Theaceae						
Camellia sinensis (L.) Kuntze (H)	> 7 years	sc	> 5.5	-	E,W	Laycock and Wood (1963)
C. sinensis (H)	8–11 years	c	4.3	-	E	Carr (1974)
C. sinensis (H)	-	Various,r	> 6.1	3.7	E	Kerfoot (1962)
Schima superba Gard. & Champ. [= *S. wallichii* (DC.) Korth.]	50 years	sil/sic,r	1.7	-	E	Yen et al. (1978)
Tiliaceae						
Tilia L. sp.	16–24 m	c	-	20.0	R	Cutler and Richardson (1981)
Tilia americana L.	28 years	c	1.6	8.2	E	Yeager (1935)
T. americana	36 cm	Till	2.1	-	O	Mueller and Cline (1959)
Ulmaceae						
Celtis occidentalis L. (W)	25 years	sil	2.5	6.1	E	Sprackling and Read (1979)
C. occidentalis	35 years	c	1.3	12.6	E	Yeager (1935)
Ulmus L. sp.	25 m	c	-	25.0	R	Cutler and Richardson (1981)
Ulmus americana L.	30 years	s,wt	6.1	> 3.7	E	Hayes and Stoeckler (1935)
U. americana	40 years	c	1.2	19.2	E	Yeager (1935)
U. americana (W)	49 years	l,sl/gr	-	34.1	E	Greb and Black (1961)
Ulmus montana With.	50 years	l	1.6	-	R	Köstler et al. (1968)
Ulmus pumila L. (W)	10 years	sicl,sl,wt	4.8	-	E	Sprackling and Read (1979)
U. pumila (W)	Mature	cl,sl	8.2	13.1	E	Bunger and Thomson (1938)
Ulmus rubra Muhl. (W)	67 years	sil	1.8	7.9	E	Sprackling and Read (1979)
Verbenaceae						
Tectona grandis L.f.	-	sil	3.9	-	E	Howard (1925)
Mixed stands						
Acer saccharum and *Fagus grandifolia*	Old	sl/c	> 2.7	-	W	Harlan and White (1968)

Mixed stands						
Acer saccharum and *Fagus grandifolia*	Old	sl/c	> 2.7	–	W	Harlan and White (1968)
Quercus spp. and *Carya* spp.	40–50 years	sil	4.0	–	E,O	Kochenderfer (1973)
Quercus spp. and *Carya* spp.	21 m	scl/sl	6.1	–	W,O	Patric et al. (1965)
Quercus spp. and *Carya* spp.	13–25 cm	si,s	> 2.4	–	W	Sartz (1972)
Quercus coccinea and *Q. velutina* Lam.	32 years	s	> 3.7	–	W	Lull and Axley (1958)
Quercus spp.	60–70 years	s	2.1	–	W	Urie (1959)
Eucalyptus signata-dominated forest	15 m	s	10.0	–	E	In Westman and Rogers (1977)
Amazonian semi-evergreen forest	30–50 m	cl	12.0	–	E	Nepstad (1989)
East African rainforest	> 21 m	cl	> 3.2	–	E,W	Pereira et al. (1962)
Surinam high forest	50–60 m	s,c,wt	> 5.0	–	E,W	Poels (1987)
Eight species windbreak	21 years	sicl/si	> 3.4	–	W	Sander (1970)
'Mallee' (*Eucalyptus oleosa*, F. Muell. ex Miq., *E. incrassata* Lavill., *E. calycogona* Turcz., *Melaleuca pubescens* Schauer)	< 8 m	s,sl/ scl,cl	≈ 18.0	–	C,O,E	G.B. Allison (personal communication, 1987)
'Mallee' (*Eucalyptus odorata* F. Muell., *E. oleosa*)	–	Alluvium	–	> 11.0	O	Cannon (1921)

[a]Mostly sedimentary accumulation during life of tree.
[b]Sprout.
Abbreviations:
Column 1: W, windbreak; H, horticultural.
Column 2: ds, diameter near soil surface.
Column 3: r, roots in rock; wt, roots below water table; s, sand; si, silt; c, clay; l, loam; gr, gravel; sl/sc, sandy loam over sandy clay, etc.
Column 5: l, actual length, not radius.
Column 6: C, core; E, excavation; O, other observation; R, review; Tr, tracer uptake; W, water uptake.

years after natural seeding; *Picea abies*, *Pseudotsuga menziesii* and *Robinia pseudoacacia* in loess were all approximately 3.7 m at age 4 years after planting.

One may assume that the gross architecture of root systems in an ideal, non-restrictive, herbivore-free medium would reveal genotypic potentials, much as are expressed by crowns. Something of this assumption colors many discussions of root forms and depths in actual soils. For example, Armson (1977) held that deep soils with little or no restriction to rooting within the solum offer no advantage to species with inherently shallow root systems such as *Picea mariana*. Gale and Grigal (1987) pointed to evidence for genetic control in the literature. They related vertical root density, compiled from literature accounts, to presumed successional status as expressed by shade tolerance classes; the maximum depth considered, however, was only 1 m.

The influence of genotypic control on potential development and structure of root systems is evident in many cross-sectional diagrams and photographs; for example, Glover (1952), Pereira and Hosegood (1962), Schultz (1972), Eis (1974, 1987) and B. Dubs (unpublished work, 1990). In particular, Jeník (1978) proposed a number of characteristic 'organizational models' for root systems of tropical trees and palms, noting, however, that features such as taproots and sinkers are developed by certain species only if 'soil layering, moisture and competition permit'.

In a contrast that is more apparent than real, the overriding influence of soil features on root form was specifically recognized by Büsgen and Münch (1929), and classification of tree species according to rooting depth was vigorously opposed by Coile (1951). Many investigations of forest species (Kerfoot, 1963; Eis, 1987), as well as of horticultural species, likewise have emphasized the controlling role of soil features rather than inherent species attributes in determining rooting depth. An evident exception, however, concerns differential ability to withstand poor aeration (Hook and Brown, 1973; Topa and McLeod, 1986; Eis, 1987) or to recover promptly after damage from such occurrences (Hook and Brown, 1973). Thus far, differential ability among tree species in penetrating compacted soils has been demonstrated only with seedlings (Minore et al., 1969; Wästerlund, 1985) but seems highly probable.

Controls on rooting depth

The record for deep root penetration appears to be Cannon's (1960) two accounts of live *Juniperus monosperma* roots at depths of 61 m or more in mines. Other extraordinary depths reported are for *Eucalyptus* sp. (60 m), *E. calophylla* (45 m), *E. marginata* (40 m), *Prosopis 'juliflora'* (over 53 m) and *Acacia raddiana* (35 m). Few other values in Table 1 exceed 20 m.

For several species studied, maximum depth of root penetration occurs immediately beneath or adjacent to the stem by either a taproot or 'sinker' roots

(Curtis, 1964; Eis, 1974, 1987). This is also the case with *Pinus elliottii* (Schultz, 1972) and perhaps several other species that depend on internal transport of oxygen to sustain roots in poorly aerated or saturated soils. In contrast, many other species, including pines, oaks, eucalyptus and *Robinia*, produce either obliquely descending roots or sinkers along the lateral roots which reach depths similar to or greater than those of the taproot and near-stem sinkers.

Adverse soil physical features, including bedrock, 'pans', dry substrates and water tables, are so widespread and so obviously influential that they must be assumed to be the major causes of shallow root penetration (Glínski and Lipiec, 1990) except where chemical barriers such as Al toxicity or salinity occur. Observation of rooting depth in small soil pits, however, often is misleading. Roots encountering layers of high soil strength or bedrock commonly end abruptly or are replaced by horizontal branches, suggesting that the maximum depth of penetration has been reached. In actuality, the limiting layer may contain various sorts of joints, shrinkage cracks, fractures, solution holes or 'soft spots' that allow sinkers to penetrate much deeper and, if conditions allow, to ramify widely. Kimber's (1974) sketch (reproduced in Armson, 1977) of an *Eucalyptus marginata* root system affords a classic example: although rooting appeared to end at a massive laterite surface at a depth of 1 m, a few roots penetrated channels and gave rise to profuse rooting above a water table at 14.9 m. Less striking but parallel instances are often seen when examining deep trenches or road cuts in well-aerated substrates. Likewise, the thicknesses of basal root plates seen on wind-thrown trees commonly underestimate the depths reached by small roots or even deep sinkers at some distance from the basal rootplate, especially where this is subject to 'rocking' by wind (Day, 1950; Stone, 1977; Coutts, 1983). As numerous authors have noted, descending roots and sometimes laterals commonly follow old root channels and other biotic tunnels, often growing through decaying wood. For example, Greenwood et al. (1981) noted that, below a depth of 2.8 m, all *Pinus radiata* roots were restricted to relic root channels of the previous *Eucalyptus* forest. Such opportunities for unhampered extension may be lost after conversion to pasture or cropland.

Rooting depth and soil water

For 47 references in Table 1, 'effective' rather than absolute maximum rooting depths were revealed by measured depletion of stored soilwater ('W' in column 6). Such depletion often reached or was near the wilting point level even though fine root densities may have been sparse (Hoover et al., 1953). Gardner and Ehlig's (1962) observations helped to rationalize such findings at a time when the extent of water movement to plant roots in unsaturated soils was not widely recognized. For ectomycorrhizal species, water transport through specialized rhizomorphs (Duddridge et al., 1980) may permit roots spaced at 10–50 cm to exploit the intervening soil without regard to matrix hydraulic conductivity, at least throughout the depths to which the symbiont occurs. The quantities of water actually removed or potentially available are sometimes large relative to periodic potential evapotranspiration; for example, 53 cm of available water in a thickness of 3.2 m (Pereira et al., 1962), about 45 cm in 3 m (Pereira and Hosegood, 1962), 42 cm in 5.8 m (Patric et al., 1965) and 90 cm in 2.7 m (Will and Stone, 1967). Patric et al. (1965) discussed patterns of water removal as related to root density over a depth range of about 6 m, and Carbon et al. (1980) to about 18 m. Many other investigators (Hayes and Stoeckler, 1935; Laycock and Wood, 1963; Teskey et al., 1978; Hinckley et al., 1979; Doley, 1981) have described the importance of deep roots for survival or sustained growth during dry periods.

Thirty references in Table 1 indicate roots in contact with water tables at depths from 1.5 to 35 m. Other reports of roots reaching permanent or recurring water tables at depths less than 2 m are common, of course, as are measurements of water table lowering through evapotranspiration. Studies with soybean (*Glycine max* (L.) Merr.) demonstrate that roots near a water table may be more effective in absorption by 1000 times or more than those in drier soil above (Reicosky et al., 1964). In yet other instances, deep roots exploit lateral flow, either saturated or unsaturated (Hewlett, 1961; Patric et al., 1965; Scholl and Hibbert, 1973), as well as slowly percolating water in horizontally fissured rocks or porous substrates such as chalk or volcanic lapilli (Will and Stone, 1967).

The previous paragraphs concern direct access to soilwater below the conventionally examined surface meter or two. Richards and Caldwell (1987) emphasized the additional factor of 'hydraulic lift', the efflux of water into dry surface soil from root systems in contact with moist soil at greater depth. The water so transferred may be reabsorbed by the same roots, possibly facilitating nutrient uptake, or may be used by associated shallow-rooted plants.

Root penetration into rock

Extension of roots into saprolite, grus, or fractured or fissured bedrock underlying shallow soils is commonplace, and their contribution to plant moisture supplies is widely assumed and sometimes measured (Tew, 1966; Fisher and Stone, 1968; Scholl, 1976). Jones et al. (1989) found roots of chaparral species over 6 m deep in weathered granite. Part of this distance was in grus that retained 2.4% (v/v) of water between -0.01 and -1.5 MPa. The overlying soil retained 8% water, but was only 20–50 cm thick.

Forty-two references in Table 1 indicate penetration of roots 2–60 m below the soil surface, with some, much, or all of the distance being in rock. A variety of rock types are represented, and eight of these references concern roots

growth pressure of a particular root varies from one time to another, or how growth pressure is affected by hormonal activity, soil chemical environment, or temperature.

II. ROOT ELONGATION THROUGH A SOIL WITH UNIFORM FABRIC

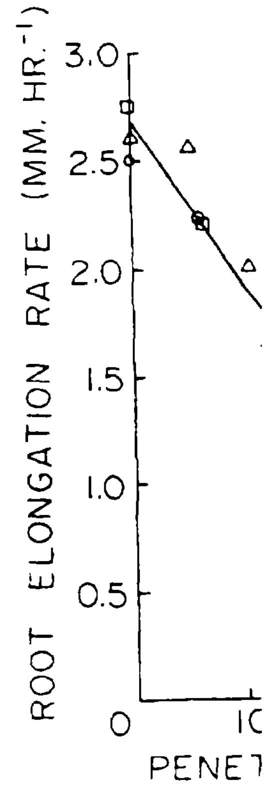
Soil fabric, which is "the physical constitution of a soil material as expressed by the spatial arrangement of the solid particles and voids" (Brewer, 1964), is extremely important in root growth. Soil fabric determines physical behavior and controls water, heat, aeration, and strength relations important in root growth.

A. Soil Strength Effects

If the soil has no continuous pores that are large in relation to the root tip, elongation rates will depend on the magnitude of the external constraint. As an example, Barley (1962) examined the ability of corn (*Zea mays* L.) roots to overcome external constraints by using an apparatus which enabled measurement of length as the roots grew. When cells differentiated and elongated while the apex was compressed, root length increased continuously, but at a rate that declined with increased mechanical stress. Taylor and Ratliff (1969b) showed that the rate of peanut (*Arachis hypogaea* L.) root elongation decreased as soil strength (measured by penetrometer resistance) around the root increased (Fig. 11.2). The elongation rate was 2.7 mm/hr when penetrometer resistance was near zero bars. At a penetrometer resistance of 15 bars, the elongation rate was about 1.5 mm/hr, and it was about 0.8 mm/hr at 30 bars. Soil water potentials between -0.19 and -12.5 bars (water contents between 7.0% and 3.8% by weight) did not affect the root elongation–soil strength relationship. The compaction process used by Taylor and Ratliff left few continuous voids that were larger than the diameter of the peanut root tip; so soil strength controlled elongation rate.

B. Soil Porosity Effects

If enough large vesicles (defined by Brewer, 1964, as voids with walls that consist of smooth, simple curves) or other large pores exist, roots can grow through high-strength material. Aubertin and Kardos (1965a, 1965b) illustrated this point by growing corn in a container



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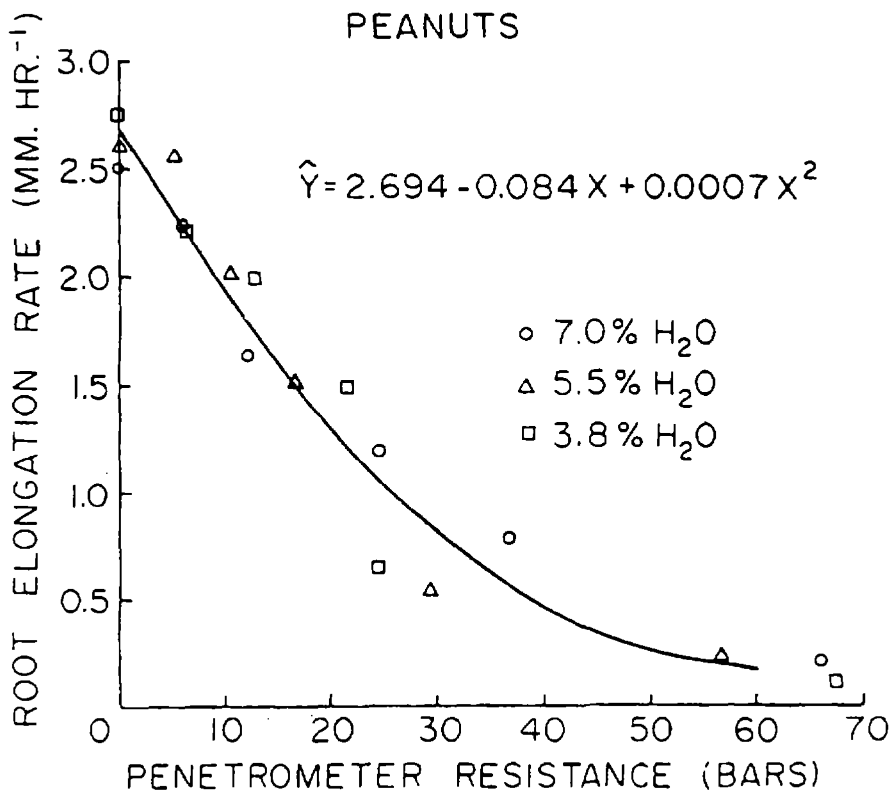
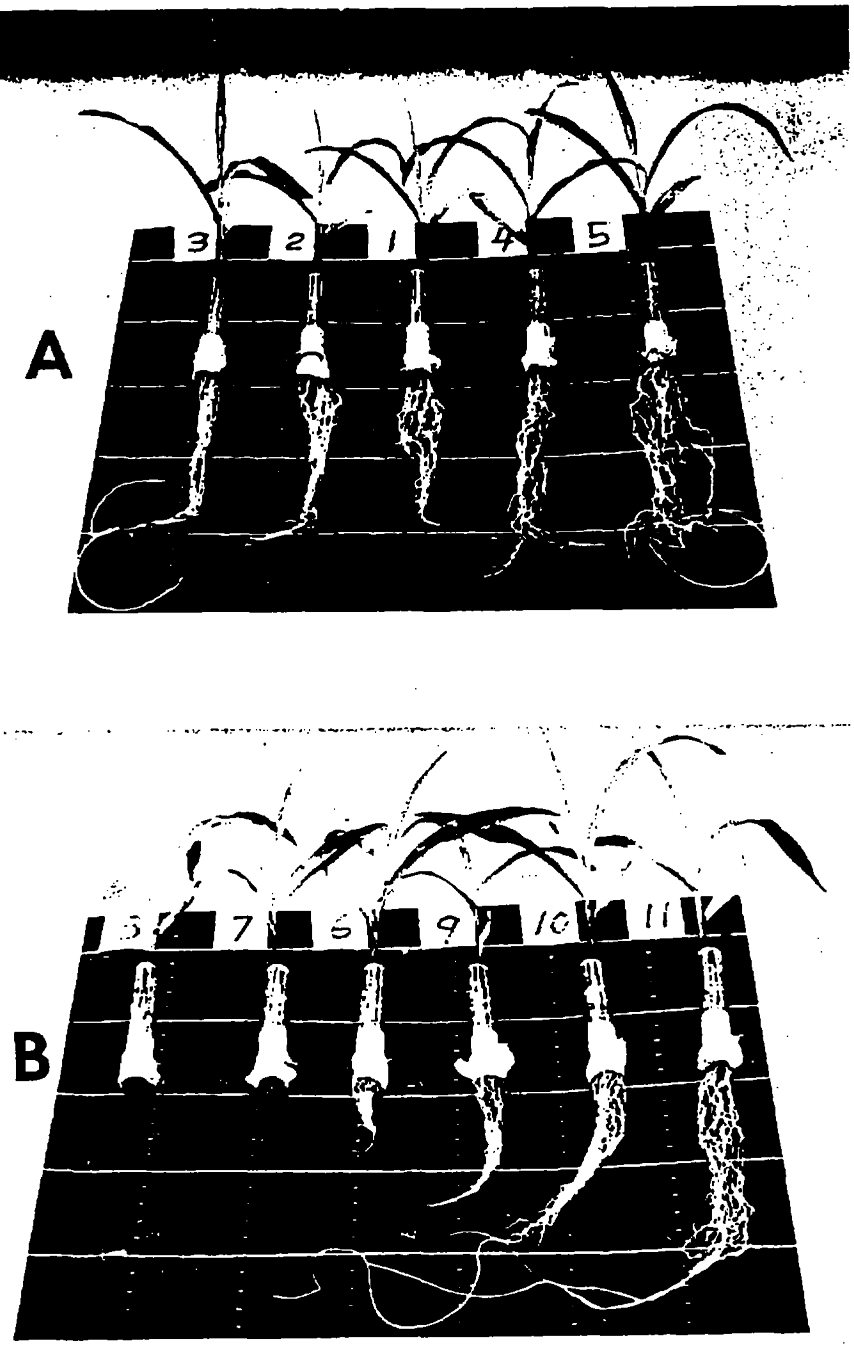


Fig. 11.2. Effect of soil water content and soil strength as measured by penetrometer resistance on peanut (*Arachis hypogaea* L.) root elongation for 40 to 80 hours after radicle emergence. (Reprinted by permission from H. M. Taylor and L. F. Ratliff, *Soil Sci.* 108: 113–19, © 1969, The Williams & Wilkins Co., Baltimore, Md. 21202, U.S.A.)

where a clamping device could alter rigidity of the glass bead matrix. Systems were used whose modal pore sizes ranged from 46μ to 412μ in diameter. In the nonrigid system, roots could grow equally well at 46μ as at 278μ (Fig. 11.3A), but corn roots did not grow into the rigid systems where pore diameters were less than 138μ (Fig. 11.3B). Any reduction in pore diameter below 412μ reduced root growth in the rigid systems.

The diameters of plant roots near the root tips vary greatly. Plants whose roots have small diameters near the tips can penetrate rigid soil volumes that roots with larger tips cannot. On the same plant, tertiary roots often act differently from tap, or seminal, roots. Sometimes their reaction is different because the tertiary roots are smaller; however, the main exploring roots also may have encountered a particular soil volume at a time when its soil water was different from that encountered by the tertiary roots.



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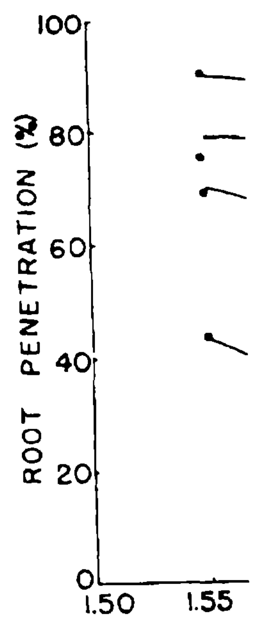

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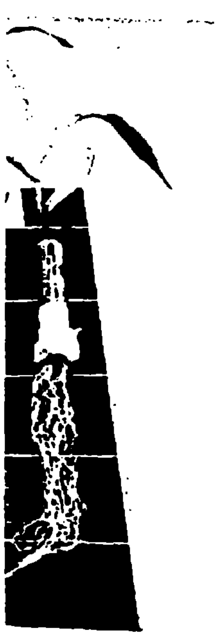

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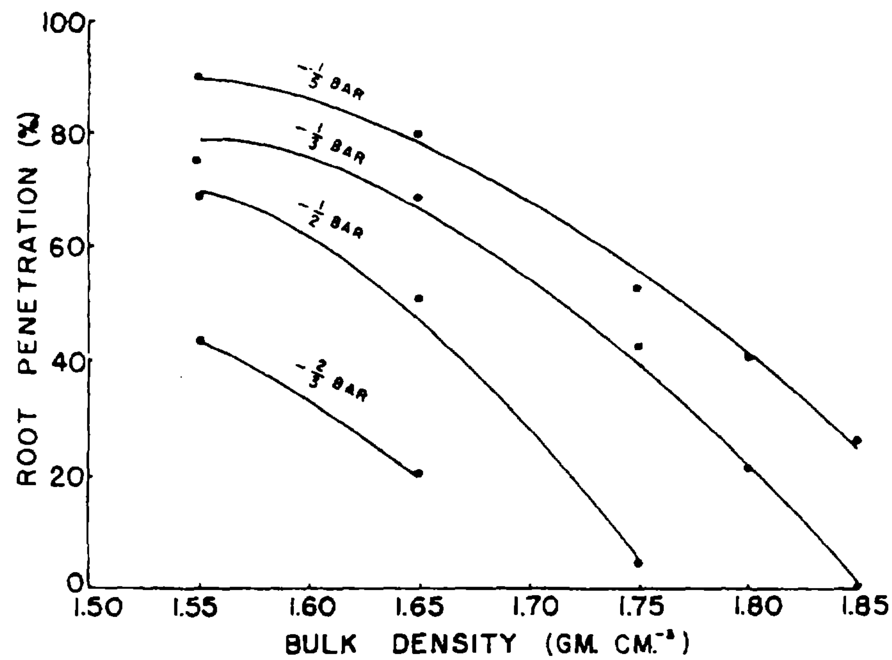
C. Systems with Both Soil Strength and Soil Porosity Effects

In most soils, roots penetrate partly by growing through existing voids and partly by moving aside soil particles (Wiersum, 1957; Aubertin and Kardos, 1965a, 1965b). When a soil is compacted, the modal pore size is reduced, soil strength is increased, and soil aeration is reduced. In a classic early experiment, Veihmeyer and Hendrickson (1948) investigated the effects on root growth of increases in soil bulk density (defined as the mass of oven-dry material per unit volume of soil). They showed that root growth decreased as soil bulk density increased, but their data did not delineate the various factors that might have caused the reduced root growth.

Taylor and Gardner (1963) found that root penetration at a particular soil water potential decreased as bulk density increased (Fig. 11.4). At a specific bulk density, root penetration decreased as soil water potential or water content decreased. They concluded that in their experiment root penetration was reduced as soil strength increased. Taylor *et al.* (1966)



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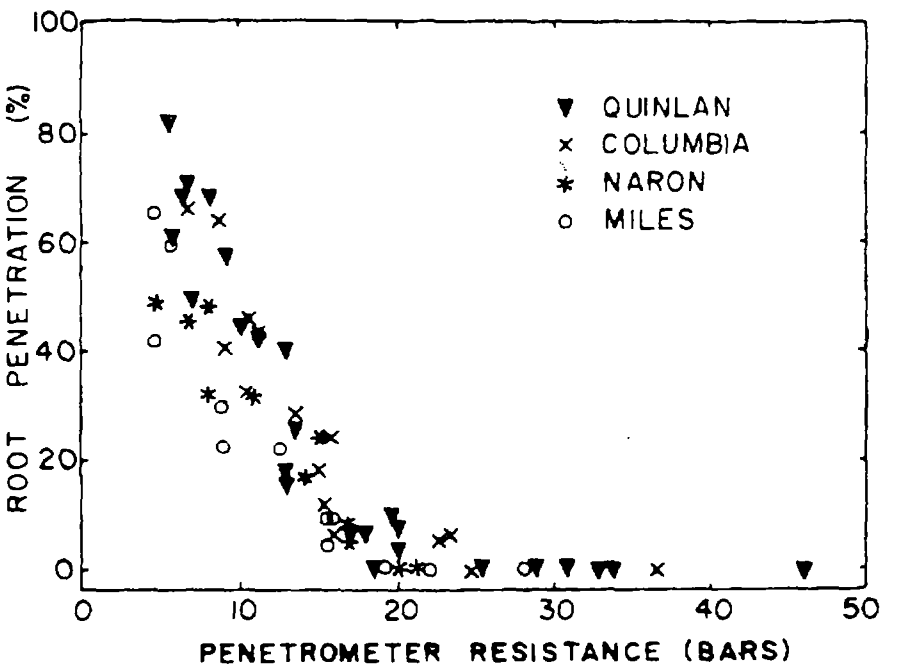

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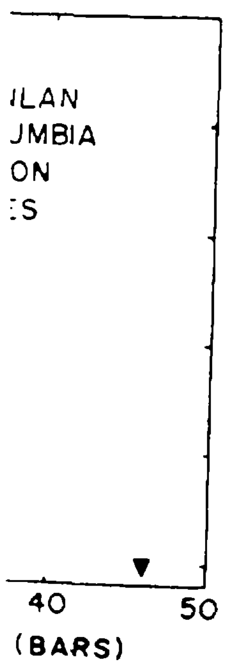

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soil with uniform fabric. When other growth factors are satisfactory, root growth decreases as soil strength increases. However, when other factors limit root growth, soil strength probably exerts little or no effect.

D. *Measurement of Soil Strength*

Soil strength is affected not only by changes in water content and soil bulk density but also by changes in types and amounts of saturating cations (Gerard, 1965), the number of particle-to-particle contacts (Lotspeich, 1964), the type of clay mineral (Grim, 1962), and the amount and type of organic materials (Jamison, 1954). Consequently, there is no simple way to predict soil strength from measurement of soil texture, organic matter, pH, or other common parameters. The American Society of Agricultural Engineers has published a standard for the design and use of penetrometers in estimating soil strength (American Society of Agricultural Engineers, 1970, ASAE Recommendation R313 Soil Cone Penetrometer, *ASAE Yearbook*, pp. 296–98). In root penetration studies the penetrometer technique is probably as useful as any other technique for assessing soil strength. However, it is emphasized that the various techniques provide different quantitative values when used on the same soil sample. These values, although quantitatively different, often are highly correlated (Taylor and Burnett, 1964).

III. ROOT ELONGATION INTO SOILS WITH WELL-DEVELOPED STRUCTURAL DISCONTINUITIES

Much of the research evaluating effects of soil fabric and soil strength on root elongation has been conducted using unusual methods to achieve uniformity, but nearly all field soils contain some structural development. Where this development has occurred, soil porosities and soil strengths vary from one volume of soil to another. As a result, physical conditions important to root growth will vary from one location to another within the soil profile.

A. *Vertical Cracking Pattern Effects*

E. Burnett (private communication) investigated the pattern of soil shear planes and plant rooting in Houston Black clay, a Udic Pellustert occurring in the Texas Blacklands. The soil has long continuous planes (sometimes greater than 2 m in length) where one block of soil has moved in

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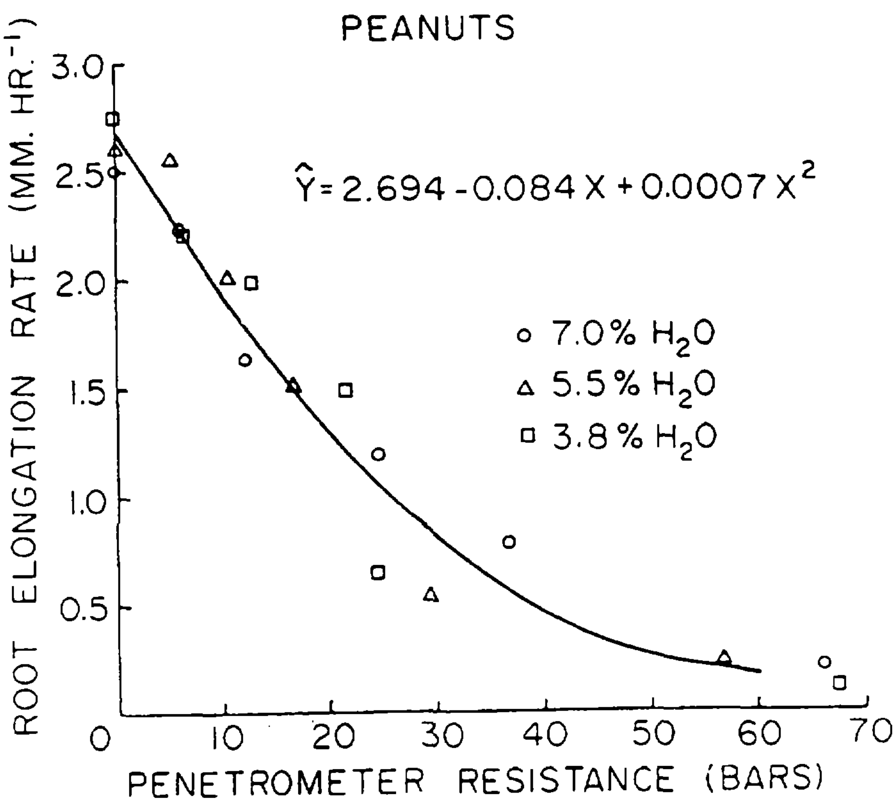

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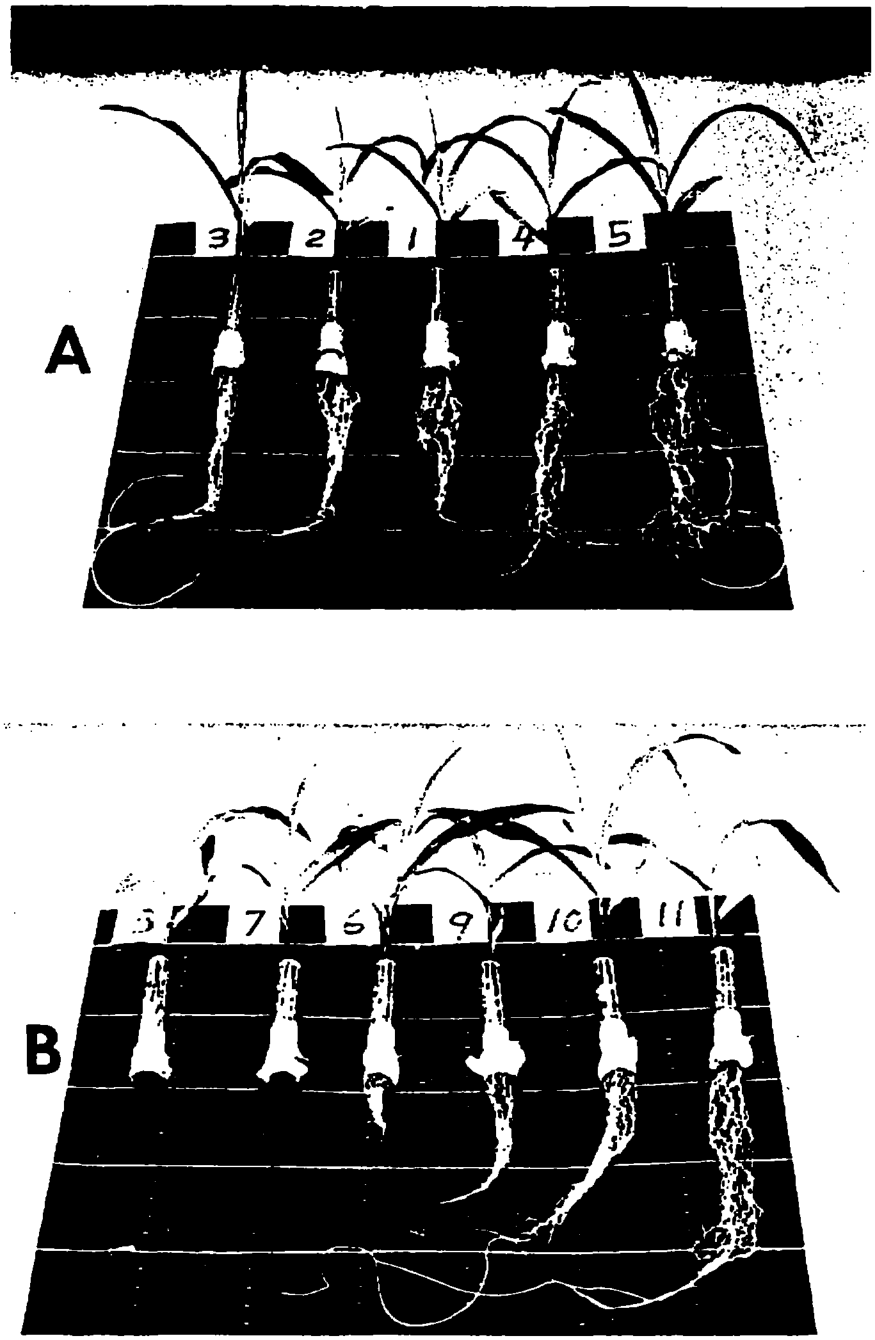

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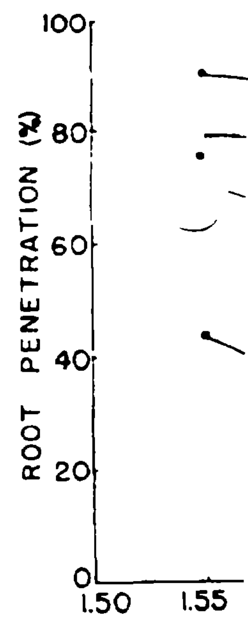

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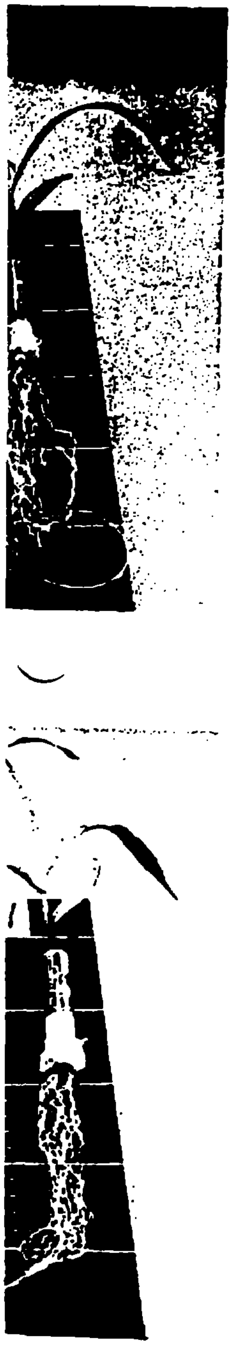

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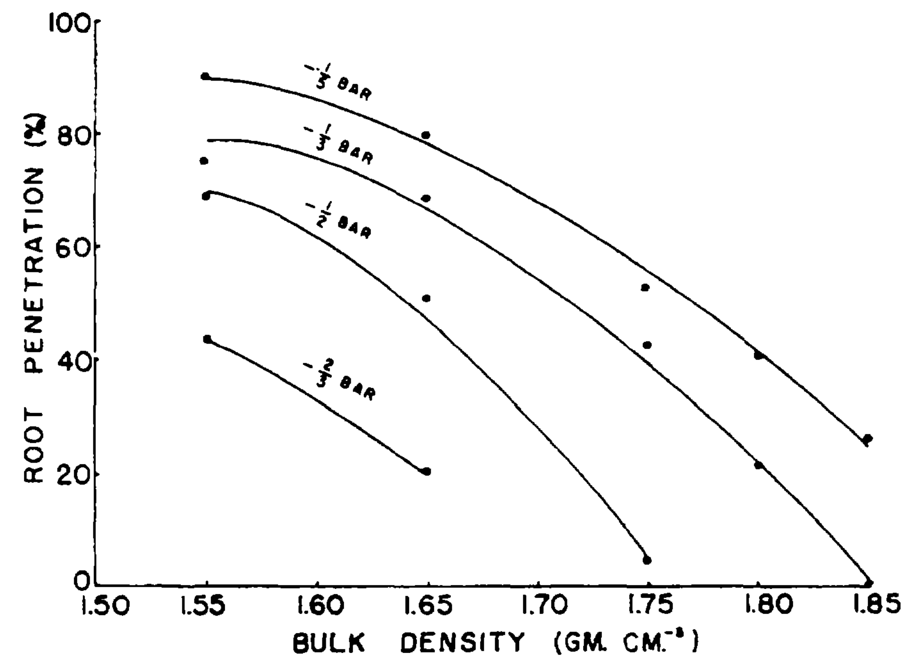

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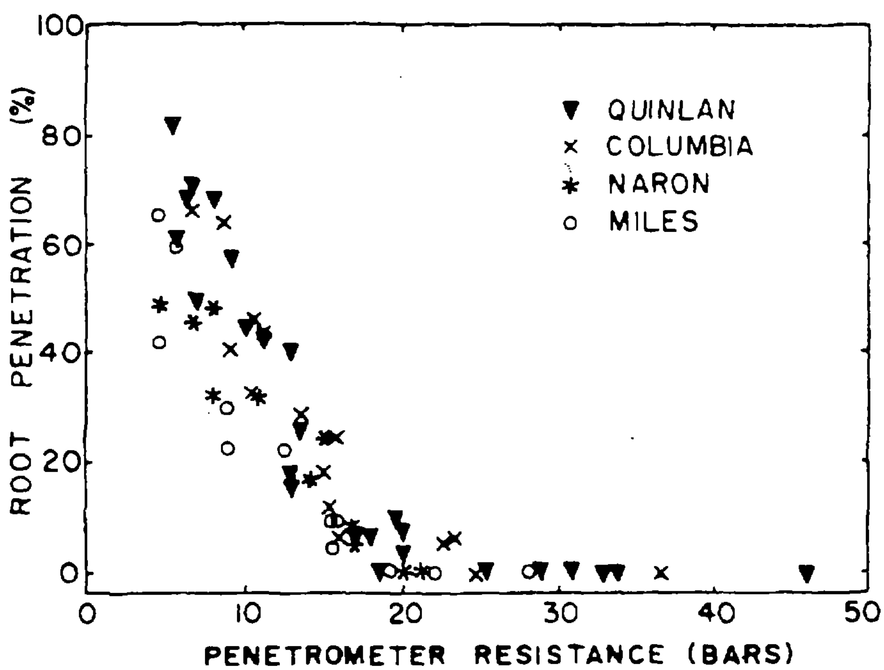

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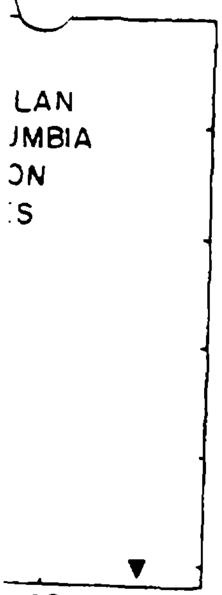

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soil with uniform fabric. When other growth factors are satisfactory, root growth decreases as soil strength increases. However, when other factors limit root growth, soil strength probably exerts little or no effect.

D. Measurement of Soil Strength

Soil strength is affected not only by changes in water content and soil bulk density but also by changes in types and amounts of saturating cations (Gerard, 1965), the number of particle-to-particle contacts (Lotspeich, 1964), the type of clay mineral (Grim, 1962), and the amount and type of organic materials (Jamison, 1954). Consequently, there is no simple way to predict soil strength from measurement of soil texture, organic matter, pH, or other common parameters. The American Society of Agricultural Engineers has published a standard for the design and use of penetrometers in estimating soil strength (American Society of Agricultural Engineers, 1970, ASAE Recommendation R313 Soil Cone Penetrometer, *ASAE Yearbook*, pp. 296–98). In root penetration studies the penetrometer technique is probably as useful as any other technique for assessing soil strength. However, it is emphasized that the various techniques provide different quantitative values when used on the same soil sample. These values, although quantitatively different, often are highly correlated (Taylor and Burnett, 1964).

III. ROOT ELONGATION INTO SOILS WITH WELL-DEVELOPED STRUCTURAL DISCONTINUITIES

Much of the research evaluating effects of soil fabric and soil strength on root elongation has been conducted using unusual methods to achieve uniformity, but nearly all field soils contain some structural development. Where this development has occurred, soil porosities and soil strengths vary from one volume of soil to another. As a result, physical conditions important to root growth will vary from one location to another within the soil profile.

A. Vertical Cracking Pattern Effects

E. Burnett (private communication) investigated the pattern of soil shear planes and plant rooting in Houston Black clay, a Udic Pellustert occurring in the Texas Blacklands. The soil has long continuous planes (sometimes greater than 2 m in length) where one block of soil has moved in relation to its neighbor. These shear planes persist from year to year at the same location. This plane of structural weakness provided a recurring path for root penetration, and roots tended to be concentrated along these shear planes (Fig. 11.6).

V. L. Hauser (private communication) found that vertical shrinkage cracks penetrated at least 5 m in Pullman silty clay loam soil at Bushland, Texas. He found living plant roots, tentatively identified as blueweed (*Helianthus ciliaris* DC), penetrating to a 9-m depth at this site. For most of this depth, the roots tended to follow the shrinkage cracks. Since blueweed is perennial, Hauser could not estimate the time required for root penetration to the 9-m depth.

B. Strong Ped Development Effects

1. Distortion of Rooting Patterns

Many soils contain a three-dimensional network of structural discontinuities. These networks separate soil volumes into peds, defined as "the individual natural aggregates consisting of clusters of primary particles, and separated from adjoining peds by surfaces of weakness which are recognizable as voids or natural surfaces" (Sleeman, 1963).

Edwards *et al.* (1964) studied corn root penetration through Weir silt loam, a Typic Ochraqualf found in Illinois. They found that large corn roots were confined to the larger spaces between peds but that many medium and small roots penetrated about one-half of the discrete peds in the claypan B horizon. Corn roots did not penetrate peds with a bulk density greater than 1.80 g/cm^3.

Fehrenbacher *et al.* (1965) compared the penetration of corn roots with those of alfalfa (*Medicago sativa* L.) through four soils derived from shale. Alfalfa roots penetrated deeper than corn roots. Most of the alfalfa roots followed cracks and cleavage planes in the shale. They cautioned that the deeper alfalfa root penetration could have occurred in the fall when the corn had completed growth.

Growing root hairs can deform clay soils (Champion and Barley, 1969). When pea (*Pisum* sp.) radicles were grown on or in a saturated molded clay, root hairs penetrated the clay mass when the initial voids ratio exceeded 1:1 (bulk density less than 1.3 g/cm^3). The pea radicles penetrated soil materials where root hairs failed to develop. Where ped surfaces are covered with "skins," root hairs must deform the peds to obtain potassium (Soileau *et al.*, 1964) and other nutrients.

Sutton (1969) found that roots of young white spruce (*Picea glauca* Voss) readily penetrated a highly structured Lucas silt loam, but the roots

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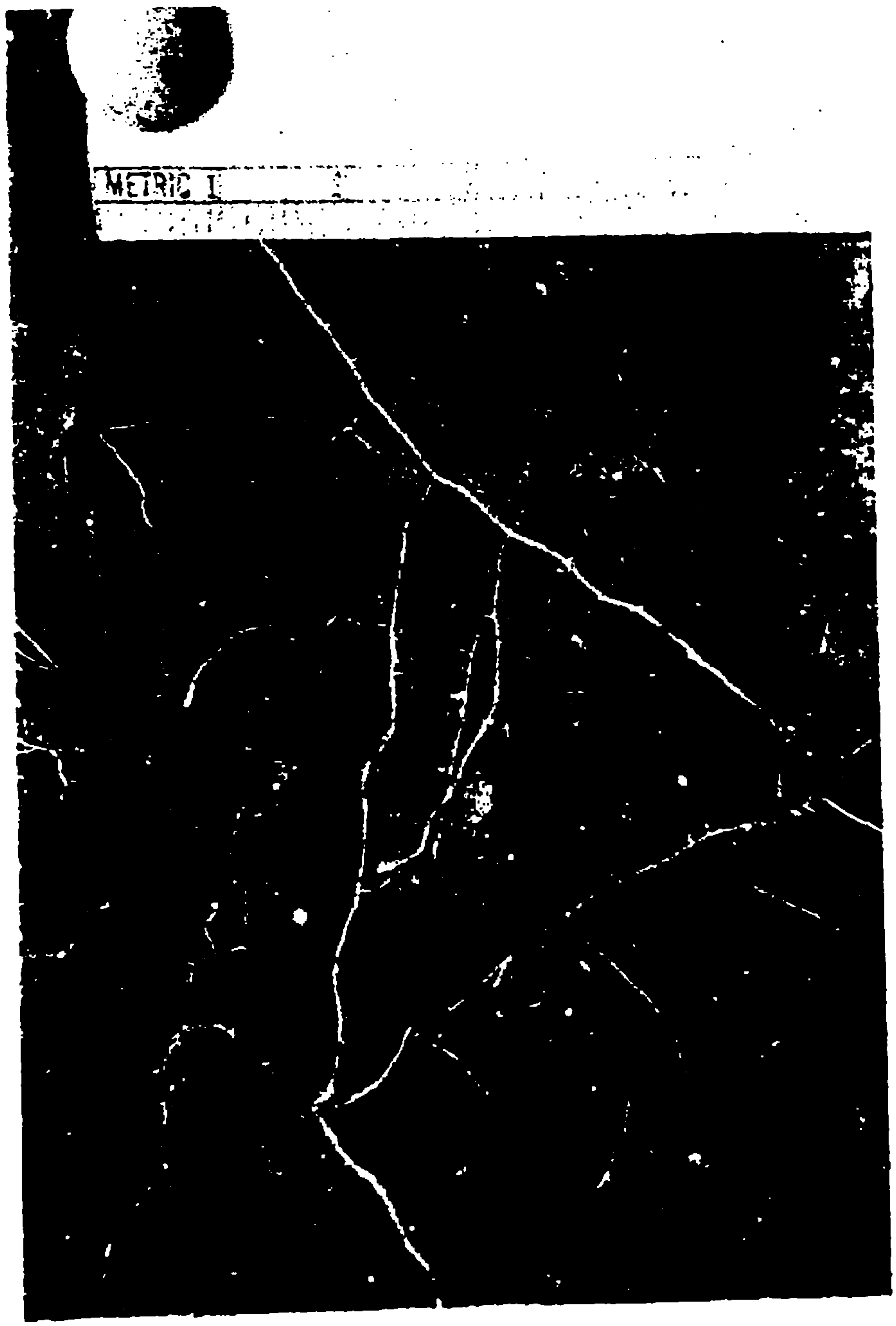
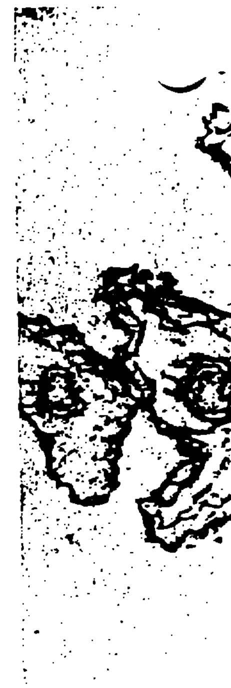


Fig. 11.6. Plant roots located in a vertical shrinkage crack of Houston Black clay. Note that the roots apparently were unable to readily penetrate the vertical face of the crack. (Photograph courtesy of E. Burnett)

Fig. 11.7. Roots of white spruce (*Picea glauca*) conforming to structural ped surfaces in a Lucas silt loam at Ithaca, N.Y. (Reprinted by permission from R. F. Sutton, *Form and Development of Conifer Root Systems*, © 1969, Commonwealth Forestry Bureau)



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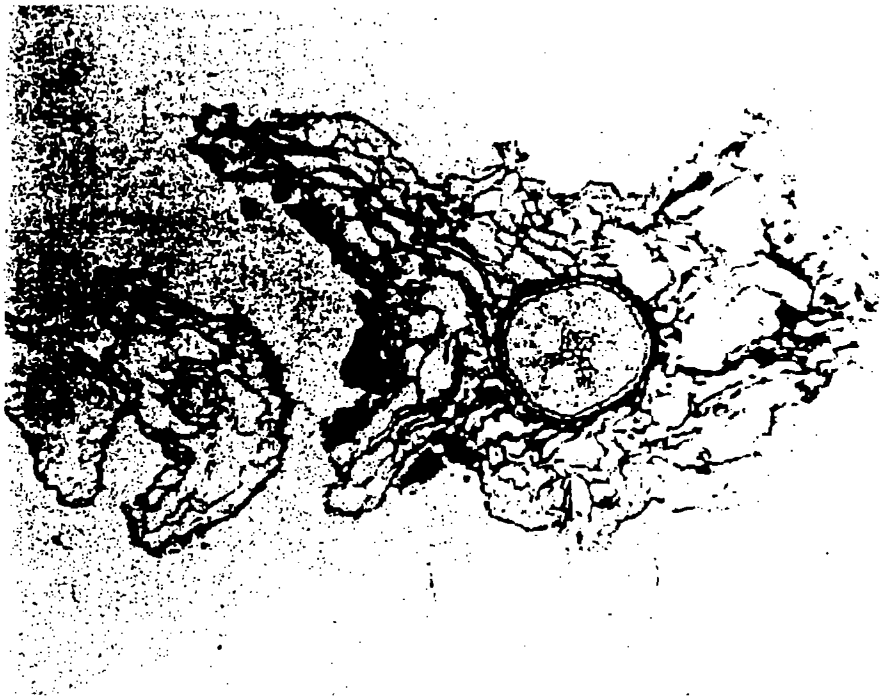

Fig. 11.8. A cross-sectional segment of three sugarcane (*Saccharum officinarum*) roots showing a badly distorted cortex. The stele shows slight distortion. Roots showing this amount of distortion are physiologically active. (Reprinted by permission from A. C. Trouse, Jr., pp. 137–52 in *12th Congr. Int. Sugar Cane Technol. Proc.* © 1965, Elsevier Publishing Company)

occurred only between structural elements. The roots were flattened in cross section, and they zigzagged, conforming with the structural element surfaces (Fig. 11.7). Misshapen roots are common in soils high in clay [illegible] (Stephenson and Schuster, 1939; Trouse, 1965). Nevertheless, these deformed roots (Fig. 11.8) are physiologically active (Trouse, 1965).

2. *Difference in Growth Conditions between Ped Surfaces and Interiors*

A word of caution is necessary here. Currie (1962) has emphasized that ped interiors and ped surfaces have different aeration relations. Therefore, one should not assume that excessive soil strength of the ped interior is the only cause of high concentration of roots at the surface. Also, water, temperature, nutrition, and pH may differ between ped surface and interior. The effects of ped size or shape on total root growth or crop yield are not known.

In structured soils, there is considerable difficulty in actually assessing the soil strength that a root must overcome to penetrate. First, most penetrometers are larger in diameter than the elongating portions of roots. Second, the root tips often have mucigel layers (Leiser, 1968), which may reduce the coefficient of friction between root surface and soil particles below that which occurs between the penetrometer tip and soil particles. Third, the root is easily deformed (Camp and Lund, 1964), but the penetrometer tip is rigid. Fourth, different types of penetrometers used in root penetration studies give different values of soil strength. Thus, measurements of media constraints with penetrometers are, at best, empirical. Measurements of soil strength and other root growth parameters should be made on a scale about equal to the diameter of the root.

C. *Horizontal Pan Effects*

1. *Rooting Patterns on Pans*

Most of the highly structured soils are fine textured. However, fabric discontinuities also exist in loams or sandier soils. Some of these horizontal layers, variously called hardpans, plowpans, tillage pans, plow soles, or tillage soles, divert roots and reduce rooting intensity below the pans. Initially, young roots grow downward through soil loosened by tillage. When they encounter a soil pan, part of the roots enter the pan and part are diverted horizontally. Roots that penetrate the pan at least 1 cm exhibit a reduced elongation rate as the soil strength increases. The roots that are diverted laterally may later encounter a vertical crack through which they can penetrate the pan (Taylor and Burnett, 1964). If no crack is encountered, the roots continue to grow horizontally along the pan surface until growth conditions change.

Soil pans sometimes restrict plant rooting to the few centimeters of soil near the surface (Fig. 11.9). As a result, the plants are subjected to extreme drought conditions in semiarid sandy soils. If soils containing pans are chiseled deep enough to disrupt the pans, plants will grow into the chisel slots but not where the soil pan still remains (Fig. 11.10). These soil pans, by reducing the depth of rooting, will reduce the quantity of water available for plant growth (Lowry *et al.*, 1970).

2. *Transitory Effects of Pans*

Effects of soil pans on root growth often are transitory and depend largely on water content of the soil pan. Taylor *et al.* (1964a) investigated

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Fig. 11.9. Root system of a pigweed *(Amaranthus retroflexus)* that grew on soil with a horizontal soil pan of excessive strength. (Reprinted by permission from H. M. Taylor and E. Burnett, *Soil Sci.* 98: 174–80. © 1964, The Williams & Wilkins Co., Baltimore, Md. 21202, U.S.A.)

17 root-restricting pans in the Southern Great Plains. They concluded that excessive soil strength caused by drying in the cohesive pan layer was the principal reason for distorted rooting patterns. If pan layers were at water contents near field capacity, most of the roots penetrated the pans. However, few roots penetrated pans that had dried below −1 or −2 bars

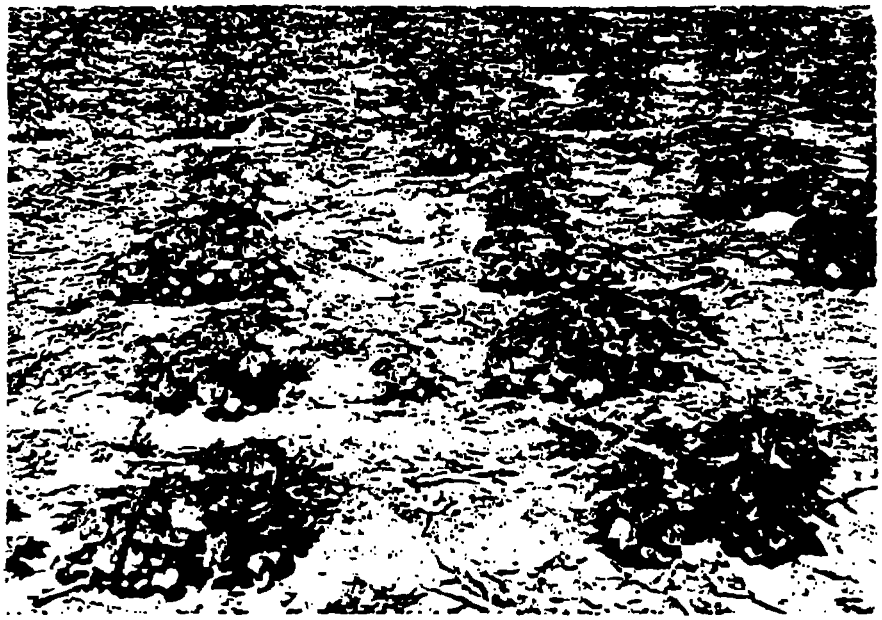

Fig. 11.10. On a compacted soil, cotton (*Gossypium hirsutum* L.) plants were established only where the planted row crossed a soil pan fracture created by chiseling to a 30-cm depth. (Taylor and Burnett, 1963)

water potential. Thus, rain or irrigation could change a root-restricting pan to a nonrestricting one. Sometimes, cotton roots penetrated pan layers that later dried sufficiently to girdle plants. If the girdling persisted long enough, the plants died (Mathers and Welch, 1964), probably as a result of reduced transport efficiency for water and nutrients (Taubenhaus *et al.*, 1931). When the pan layer was rewet, the roots again expanded radially (Taylor *et al.*, 1964a).

3. Crop Growth Effects

The root and shoot systems of a plant are dependent on and competitive with each other. Roots absorb water and minerals; leaves provide photosynthates and growth compounds. The proportion of the total supply of water, minerals, photosynthates, and growth compounds used by a particular organ changes with the environment. Therefore, the effect of a given level of soil strength will vary from environment to environment.

Consider a soil pan at a 15-cm depth which is rigid and has no pores larger than the rootcap. If the 15-cm depth above the pan can readily supply the plant's demand for water and nutrients without altering the heat or osmotic balance, yield should not be reduced below that of a nearby soil containing no pan. Similarly, soil pan strength or porosity

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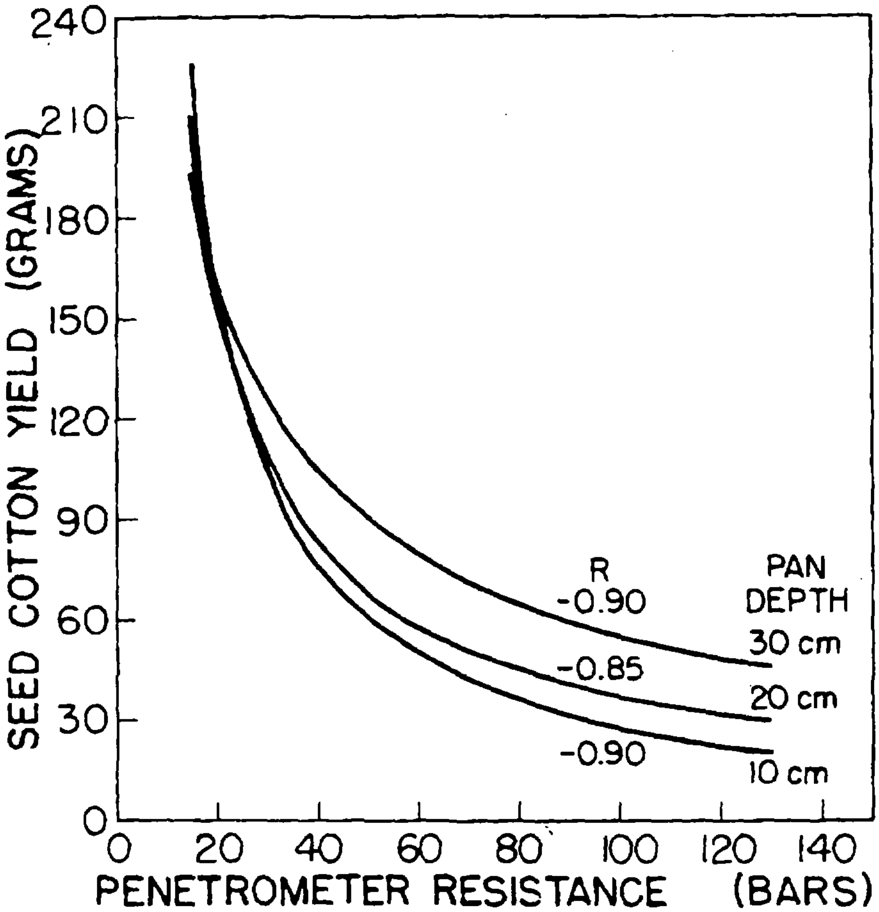

Fig. 11.11. Relations among soil pan depth, penetrometer resistance of the soil pan 48 hours after wilting, and seed cotton (*Gossypium hirsutum* L.) yield. (Lowry *et al.*, 1970)

Soil structure can be extremely important to root growth in fine-textured soils, but soil strength usually is more important than soil structure in sandy soils. If roots encounter zones of high soil strength, elongation will be reduced. However, there is no direct, simple relationship between root growth and top growth. In many cases, a small proportion of the plant top is harvested and marketed, so there may not be even a simple, direct relationship between plant tops and yield of marketable product. Excessive soil strength usually reduces yield of marketable product by causing plants to undergo additional stress for water or nutrients at critical times. Effects on yield of the various types of structural discontinuities found in fine-textured soils have not been studied extensively.

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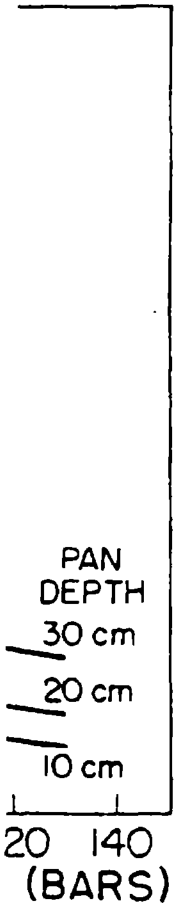

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INFLUENCE OF SOIL STRENGTH ON THE ROOT-GROWTH HABITS OF PLANTS

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United States Department of Agriculture[1]

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Recent laboratory investigations by Taylor and Gardner (8) indicate that it is soil strength, and not soil bulk density nor any other physical factor of soil, that actually controls the penetration of cotton taproots through cores of Amarillo fine sandy loam soil at ⅓- to ⅔-bar soil moisture tension. When soil strength (as measured with a soil penetrometer) is greater than 30 bars, no roots penetrate the cores. When the strength is less than 30 bars, the percentage of the roots that penetrate the soil is inversely proportional to soil strength.

Field experiments relating plant rooting habits to compactness and strength of Amarillo fine sandy loam soil were conducted during the 1959 and 1961 growing seasons at the Big Spring, Texas, Field Station. In this report, results of the two field investigations are evaluated and the critical soil strength concept is examined for applicability to several types of plants grown under field conditions.

The surface horizon of Amarillo fine sandy loam soil (A_p) is brown to reddish brown fine sandy loam; single-grained or weakly granular structure; friable when moist but hard when dry; neutral to alkaline in reaction; and 20 to 35 cm. thick. The subsoil (B_2) is reddish brown sandy clay loam; weakly prismatic and subangular blocky structure; friable when moist but very hard when dry; neutral to slightly alkaline in reaction; and 60 to 110 cm. thick. A more detailed description of the soil and some discussion of the climate has been published elsewhere (3).

PROCEDURE

1959 Experiment

In December, 1958, four plots, 4.5 by 7.7 m., separated by alleys 2 m. wide, were diked and flooded with 10 cm. of water. For comparative purposes, two plots were left at field density. Some 18 hours after the irrigation, soil of the other two plots was compacted by driving a 3840-kg. wheeled tractor twice over each part of the plot. After 4 days, the compaction process was repeated. The tractor tires left tracks 5 to 8 cm. deep during the first two trips, but during the compaction 4 days later, the tires did not materially sink into the soil.

On May 10, 1959, rows of cotton (*Gossypium hirsutum*), sesame (*Sesamum indicum*), guar (*Cyamopsis tetragonolobus*), sesbania (*Sesbania exaltata*), mung beans (*Phaseolus aureus*), cowpeas (*Vigna sinensis* var. Chinese Red), and sorghum (*Sorghum vulgare* var. Sumac Sorgo) were planted on all four plots. No seedbed was prepared, but the planting operation disturbed soil to a 5-cm. depth. Because of damage from blowing sand, part of the area was replanted in early June.

To sustain vegetative growth on the compacted plots, on July 5 a 5-cm. irrigation was applied by sprinklers to all plots. In July, quintuplet bulk density samples were obtained by depth increments, using a Pomona sampler (1).

1961 Experiment

To eliminate any previous compaction, the soil was disk-plowed to a 25-cm. depth and irrigated sufficiently to wet the upper 60 cm. When the soil was dry enough to support it, a 5500-kg.-weight road roller was driven twice over the surface of half the plots.

When the compacted soil was dry enough to shatter appreciably by chiseling, tillage variables were installed on all plots, both noncompacted and compacted. These treatments were (*a*) no tillage, (*b*) chiseling 25 to 30 cm. deep on 100 cm. centers, (*c*) disk-plowing to 25 cm., and (*d*) sweep tillage 10 to 15 cm. deep.

Cotton (*Gossypium hirsutum* var Western Stormproof) was planted with a double-disk surface planter on May 22, 1961. There was

[1] Southern Plains Branch, Soil and Water Conservation Research Division, Agricultural Research Service, Southwestern Great Plains Field Station, Bushland, Texas, and Blackland Conservation Experiment Station, Temple, Texas.

no cultivation after planting; v
Numerous rooting-habit observ
during the growing season. After
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In July, 1961, soil strengt
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RESULTS

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[2] Model 719-40, John Chatillon
St., New York, N. Y. (Product and
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no cultivation after planting; weeds were hoed. Numerous rooting-habit observations were made during the growing season. After harvest, 10 root systems from each tillage treatment were dug by depth increments, washed free of soil, dried, and weighed.

In July, 1961, soil strength measurements were made by two different procedures: (*a*) in situ measurement of vane strength (4, 6), using a 5-cm.-wide, 5-cm.-high vane while the soil was at field capacity; and (*b*) in situ measurement of soil strength made by pushing the 0.48-cm. cylindrical-diameter tip of a Chatillon force gauge[2] 0.5 cm. into the soil at field capacity.

RESULTS

1959 Experiment

In 1959 the tractor tire traffic caused significant changes in soil compaction that extended through the 30-cm. depth (table 1). The highest bulk densities, 1.73 cm.³ in the noncompacted and 1.88 g./cm.³ in the compacted plots, occurred in the 10- to 15-cm. depth.

On the compacted plots, nearly all of the plant roots were prevented from penetrating through the 10- to 15-cm. depth. A few roots did penetrate to greater depths, but these roots grew through cracks or fissures in the compacted zone. In several instances these cracks extended from the 5-cm. depth through the 20-cm. depth. In a majority of instances, a plant root grew laterally until it encountered a vertical channel, which the root followed until it encountered another impeding layer. On a number of roots of larger diameter, 3 to 5 successive turns of approximately 90 degrees occurred within a 50-cm. length of root.

A few roots of all species eventually penetrated the compacted layer by following available cracks, but no differences could be observed among species in their ability to penetrate the compact layer. Even the roots of pigweed (*Amaranthus retroflexus*), a taprooted weed, could not penetrate the most compact zone (fig. 1).

[2] Model 719-40, John Chatillon & Sons, 85 Cliff St., New York, N. Y. (Product and company name is included for the benefit of the reader and does not infer any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.)

TABLE 1
Effect of compaction treatment on the soil bulk density of Amarillo fine sandy loam (1959 experiment)

Depth	Noncompacted	Compacted
cm.	*g./cm.³*	
0–5	1.50	1.75
5–10	1.40	1.80
10–15	1.73	1.88
15–20	1.60	1.80
20–25	1.71	1.75
25–30	1.63	1.75

FIG. 1. Root system of a pigweed plant that grew on soil with a zone of excessive strength.

Soil of the noncompacted plots contained a moderate soil pan that had developed during previous years. When the soil of these plots was near field capacity, most of the roots of all species could penetrate the pan, even without the aid of a soil crack. When soil of the most compact zone was still within the available water range but near wilting point, the plant roots did not grow through the soil mass.

1961 Experiment

Average bulk density of the 10- to 15-c depth in the compacted plots again was 1.85

g./cm.³ in 1961 (table 2). The horizontal variations in bulk density, however, were much less in 1961 than in 1959.

The various tillage treatments caused quite different reactions in the compacted soil. Disk tillage effectively pulverized the compacted soil, but chisel tillage tended to plow a trench about 15 to 25 cm. wide at the soil surface rather than to shatter the entire soil volume. Sweep treatments were difficult to establish because sweeps either tended to penetrate too deeply or did not penetrate the high-strength soil surface.

Establishment of the cotton seedlings varied with the compaction and tillage treatments. Although an adequate number of plants emerged on all plots, a few weeks later the seedling plants began to die on plots where the compacted soil was not disrupted by any tillage. Most of the plants died on the compacted no-tillage plots. On plots that were compacted and then chiseled the seedling plants survived where the planted rows crossed a chisel trench but died in the area between chisel trenches. Plant establishment was adequate on all noncompacted plots and on the compacted plots that were later sweep- or disk-plowed prior to planting.

Effects of soil compaction on rooting habits of cotton were very striking (fig. 2). Compaction of the soil, if not subsequently loosened by a tillage operation, caused a marked reduction in the weight of roots that developed in the soil layers below 15 cm. (table 3). Distribution of roots between the various soil depths also was affected. On noncompacted plots about 70 per

TABLE 2

Effect of compaction and tillage treatments on bulk density of Amarillo fine sandy loam soil (1961)

Depth	Non-compacted, No Tillage	Compacted				
		No tillage	Swept to 10 cm.	Disk-plowed to 15 cm.	Chiseled	
					Between slots	In chisel slots
cm.	g./cm.³					
0-5	1.80	1.75	1.03	1.50	1.76	1.70
5-10	1.00	1.88	1.00	1.00	1.80	1.72
10-15	1.01	1.88	1.83	1.73	1.80	1.00
15-20	1.07	1.84	1.84	1.08	1.84	1.61
20-30	1.72	1.72	1.65	1.08	1.67	1.62

FIG. 2. Root systems of cotton grown on plots (*left*) that were not compacted but were sweep tilled 10 cm. deep, and (*right*) that were compacted and sweep-tilled 10 cm. deep in 1961.

cent of the root weight was in the upper 15 cm. of soil. On the compacted plots that were sweep-tilled, root percentage within the upper 15 cm. of soil was increased to 89 per cent. Between chisel marks on compacted plots, the entire root system weighed much less than on the noncompacted plots, but the percentage of roots within the upper 15 cm. decreased to 55 per cent. A root system within the chisel trench, however, weighed more than it weighed under any other condition. Part of the moisture within the nonchiseled soil was available for growth of plants established on or near the chiseled portion of the soil volume.

Compaction and tillage treatments affected soil strength as measured with a penetrometer (table 4). When this soil was compacted, soil strength increased. When the compacted volume of soil was tilled, the strength decreased. A relationship between bulk density, soil moisture tension, and soil strength for Amarillo soil at this site is published elsewhere (8).

On August 6, heights of cotton plants grown on the compacted–no-tillage and on the compacted–sweep-tilled plots were significantly different (at the 5 per cent level) from those of plants grown on any other treatment (table 5).

The differences in root growth also caused significant differences in lint cotton yield (table 6). *Lint yield* on the compacted-nontilled plots was less than half that of the noncompacted plots, regardless of the tillage treatment on the noncompacted plots. Yield of the compacted

Effect of compaction

Depth	Noncompacted	
	Root weight	Root distr
cm.	g.	%
0–15	4.98	70.
15–30	1.53	21.
30–45	0.86	5.
45–60	0.19	2.
Total in 60 cm.	7.08	100.

Each weight is the average

TABLE 4

Effect of compaction and tillag
Amarillo fine sandy loam soil stre
with a penetrometer (

Depth	Non-compacted, No tillage	Comp		
		No tillage	Swept to 10 cm.	Disk to 15
cm.	10⁶ dynes/			
0	2.8	4.1	2.8	8
5	4.1	25.5	5.5	8
10	8.8	16.5	20.9	7
15	8.3	13.8	27.6	8
20	8.3	10.4	22.0	7
25	8.3	13.1	21.4	17

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DISCUSSION

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TABLE 3

Effect of compaction and tillage treatments on cotton-root distribution (1961)

Depth	Noncompacted*		Compacted*							
			No tillage		Sweep tillage		Chisel tillage			
							In chisel marks		Between chisel marks	
	Root weight	Root distri.	Root weight	Root distri.	Root weight	Root distri.	Root weight	Root distri.	Root weight	Root distri.
cm.	g.	%	g.	%	g.	%	g.	%	g.	%
0–15	4.98	70.3	2.63	86.5	3.53	89.1	7.66	71.7	0.79	55.2
15–30	1.55	21.9	0.14	4.6	0.15	3.8	2.19	20.5	0.14	9.8
30–45	0.36	5.1	0.20	6.6	0.17	4.3	0.56	5.3	0.31	21.7
45–60	0.19	2.7	0.07	2.3	0.11	2.8	0.27	2.5	0.19	13.3
Total in 60 cm.	7.08	100.0	3.04	100.0	3.96	100.0	10.68	100.0	1.43	100.0

* Each weight is the average of 10 determinations.

TABLE 4

Effect of compaction and tillage treatments on Amarillo fine sandy loam soil strength as measured with a penetrometer (1961)

Depth	Noncompacted, No tillage	Compacted				
		No tillage	Swept to 10 cm.	Disked to 25 cm.	Chiseled to 30 cm.	
					Between slots	In slots
cm.	10^6 dynes/cm.^{2}					
0	2.8	4.1	2.8	3.3	5.5	2.8
5	4.1	26.5	5.5	3.4	24.8	5.5
10	8.3	16.5	26.9	7.6	20.7	6.2
15	6.3	13.8	27.6	8.3	17.9	4.8
20	8.3	10.4	22.0	7.6	15.8	8.4
25	8.3	13.1	21.4	17.2*	15.8	3.4

* Moisture content was below field capacity. All other measurements were made while moisture content was approximately field capacity.

than sweep-tilled plots also was significantly lower than those of the noncompacted plots.

DISCUSSION

Results of the two experiments show clearly that soil compaction altered the rooting patterns of cotton and other types of plants. During both years, the cotton seeds germinated, and unless

TABLE 5

Effect of compaction and tillage treatments on cotton height (August 8, 1961)

Treatment	Compacted*	Noncompacted*
	cm.	
None	38 a	55 d
Sweep-plowed	45 b	58 cd
Chiseled	53 c	64 d
Disk-plowed	59 cd	64 d

* Letters denote significance at 5 per cent level, using Duncan's multiple range. Means followed by the same letter do not differ significantly.

TABLE 6

Effect of compaction and tillage treatments of Amarillo fine sandy loam soil on lint cotton yields (1961)

Tillage Treatment	Compacted*	Noncompacted*
	g./m.^{2}	
None	10.1 a	43.5 c
Sweep plowed to 10 cm.	35.5 b	45.3 c
Chisels on 100-cm. centers	48.5 c	43.7 c
Disk plowed to 25 cm.	40.0 bc	42.0 c

* Letters denote significance at 5 per cent level. using Duncan's multiple range. Means followed b the same letter do not differ significantly.

diverted or impeded by a compacted soil layer, the taproots grew downward. The root diversion nearly always occurred at the plane between compacted and loosened soil.

Fountaine (5) stated that degraded soil structure affects plant growth through its effect on soil-water, soil-air, or soil-heat relations, or through its effect on mechanical impedance of a soil. Each of these possibilities will be analyzed to determine the reason that soil compaction altered plant rooting in these two experiments.

Moisture content on a volumetric basis is increased by compaction if a soil is sufficiently unsaturated (2). Moisture content on a weight basis at a stated moisture tension also may be altered (9). In the current studies, neither of these two effects of compaction on soil-moisture relationships seemed important in determining the rooting habits under the particular set of environmental conditions.

In 1961, plots were wetted thoroughly and allowed to drain for several days before the compaction and tillage variables were imposed. Soil moisture at planting time was adequate for normal germination, seeding establishment, and early development of cotton on noncompacted plots. Although some differences among plots were observed in the amount of runoff from the rains that occurred (table 7), it is doubtful that the differences in water intake rates would have caused the change in the cotton rooting patterns. Selected isolated cotton plants were watered every few days to further test

TABLE 7

Seasonal precipitation during 1959 and 1961 (U. S. Dep. Agr. Big Spring Field Station, Big Spring, Texas)

Month	1959	1961
	cm.	
April	1.60	0.03
May	9.65	2.08
June	12.62	13.97
July	11.33	16.51
August	4.95	0.23
September	3.40	8.15
October	0.41	0.51
Total	43.96	41.48

the hypothesis that it was soil strength, and not any of the soil-water relations, that was the principal factor limiting root growth. Since this additional water did not noticeably change the cotton-rooting patterns, it was concluded that neither the moisture retention nor the moisture transmission effects of soil compaction caused the change in rooting pattern.

Soil compaction reduces both the total air capacity of a soil at field capacity and the air transmission rate of a soil (10). Although either of these effects could reduce soil aeration, the possibility in the current experiments that lack of adequate aeration caused the decreased top and root growth is remote. This conclusion is based on:

1. At field capacity and at a bulk density of 1.80 g./cm.^{3}, the total air porosity of this fine sandy loam soil is about 15 per cent of the soil volume. Baver (2) and Vomocil and Flocker (10) state that 10 per cent by volume aeration porosity is about the critical level.

2. In most instances, there was a very sharp boundary between soil zones where roots penetrated satisfactorily and those zones where few or no roots penetrated. The boundary between adequate and inadequate aeration could not have been that sharp in this soil.

3. The root-growth impedance occurred more frequently and was more severe when the soil moisture content decreased within the available range. If soil aeration were the limiting factor, root growth within the compacted layer would become more profuse as the soil moisture content decreased toward the wilting point.

Since differences in soil temperatures were minor and erratic between the zones where roots could penetrate and those soil zones where roots were excluded, it was concluded that any effects of soil compaction on heat capacity and heat flow had not caused the altered rooting patterns.

Wiersum (11) suggested that a plant root growing into a rigid system is only able to penetrate a pore that has a diameter exceeding that of the root tip. Previous research, however, using wax substrates (7), has shown that cotton roots readily grow into and through 2 or 3 cm. of wax if this nonporous substrate is not too rigid. Thus, soil compaction reduces cotton-root penetration by increasing strength of the soil in which pores are located rather than by reduc-

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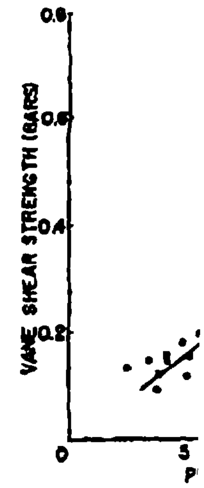

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ing the size of the pores below some critical diameter.

Both visual observations and the root weights in table 4 showed that the rooting habit of cotton was drastically affected by the high-strength layer. On the plots that were compacted but not subsequently tilled, very few roots penetrated soil layers below 15 cm. The highest soil strength encountered to that depth was 25.5 bars at the 5-cm. depth. In the sweep-tillage plots, the roots apparently penetrated easily to the 10-cm. depth and then were impeded by the layer with the 26.9 bars strength. Between the chisel marks in the compacted and then chiseled plots, the roots did not grow to any appreciable extent where the soil strength was 24.8 bars. At the 30-cm. soil depth under the compacted part of the chiseled plots, some roots were present. Apparently these roots penetrated the soil through the chisel mark and then spread laterally into the soil with a strength somewhat less than 15.8 bars.

Since, during 1959, no strength readings were made with a comparable strength-measuring device, no direct comparisons between results of the two experiments can be made. An indirect comparison, however, can be made by using soil bulk densities. In both years the highest recorded bulk density was 1.88 g./cm³. This density gave strength readings of 26.9 and 27.6 bars in the 1961 experiment and, from extrapolating a published curve (8) for strength of Amarillo soil at ⅓-bar soil moisture tension, about 28 bars in the laboratory experiment. In 1959, therefore, roots of several crops were prevented from penetrating soil at a strength of about 28 bars, but could penetrate soil with a soil strength reading of about 19 bars (field capacity at a bulk density of 1.73 g./cm.³).

Thus, the field experiments tend to verify the conclusions from the laboratory experiment (8), that excessive soil strength affected the rooting habit of cotton. In addition, the field experiments confirmed that the critical limit for this soil was about 25 to 30 bars soil strength as measured by one specific penetrometer.

Without further evidence, many workers might question the advisability of using a penetrometer as a measure of soil strength. As a check, soil strength as measured with a penetrometer was plotted against soil strength as measured with the vane shear strength procedure (fig. 3). In calculating vane shear strength, it was assumed that (a) the s sheared along the surface of a cylinder who diameter and height were equal to that of the vane, and (b) the distribution of shear stress was uniform across the bottom of the cylinder. Although magnitudes of soil strength vary greatly between the two procedures, the correlation coefficient of +.97 indicates that results from either procedure can be used satisfactorily to predict plant-rooting behavior through high-

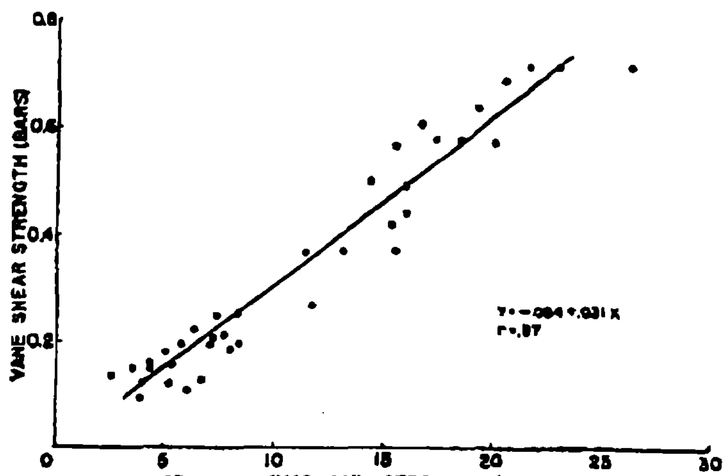

FIG. 3. The relationship between soil strength as measured with a soil penetrometer and that measured by the vane shear strength procedure.

strength soil. The penetrometer was more convenient to use in these experiments.

SUMMARY

Two field experiments were conducted to evaluate the mechanism that causes moist compacted Amarillo fine sandy loam soil to impede plant-root growth.

The results show that it is soil strength, and no other physical factor of the soil, that controls growth of roots through this moist soil. Soil strengths, as measured with one specific penetrometer, of 25 to 30 bars at field capacity prevent root penetration through the soil mass, but roots will grow through a soil layer with a strength at field capacity of about 19 bars. A few roots penetrated layers of 25 to 30 bars soil strength by following low-strength fissures or cracks.

There were no apparent differences among several species of plants in their ability to penetrate high-strength layers.

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MATERIALS AND METH

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Relative Penetrating Ability of Different Plant Roots[1]

Howard M. Taylor and Herbert R. Gardner[2]

SYNOPSIS. In a laboratory study the penetrating ability of plant roots varied with the plant species. Penetrating abilities of legume roots were not significantly greater than those of nonlegumes.

MANY investigators have reported that legume crops benefit soil physical conditions (3, 8). Some have indicated that legume roots will, under certain conditions, penetrate compact subsoils. Measurements have shown increases in total porosity, numbers of large pores, water intake rates, and root penetrability of soil layers permeated by legume roots. At times, however, negative results have been obtained when legumes were used to relieve compacted soil conditions.

Statements frequently appearing in published technical literature (2, 3, 4, 7, 8, 9, 10, 11, 12) attribute improvements of soil physical condition to an ability of legume roots to penetrate soil horizons that roots of some other types of crop plants cannot penetrate.

Significant changes in soil physical conditions can be expected from any type of root system only if the roots penetrate and thoroughly permeate a given soil layer. Obviously, the greater the number of roots that can penetrate a soil mass, the greater the opportunity for soil improvement. If all other factors are equal, plants with profuse root branching characteristics should provide more improvement in soil physical condition than plants with moderate branching characteristics.

To penetrate a soil layer, an individual plant root must grow into and through an available void larger in diameter than the root tip (15), the root must become sufficiently deformed to penetrate through an available void, or the root must exert sufficient force to create a path through the soil material by moving soil particles.

When pores or voids are present in a substrate, their size, continuity, and tortuosity are extremely important in penetration of plant roots. In addition, rigidity of the void or pore walls largely determines whether a pore can be expanded by a root tip with nonporous substrates.

Recent research (13) with nonporous substrates indicates that certain plant roots can penetrate 2 or 3 centimeters of selected waxes. Plant roots may grow into and through this depth of wax depending upon the coefficient of mobility of the wax material, the species of plant, and the amount of anchorage of the root above the root tip.

Other investigators have concluded that root growth pressures depend on oxygen supply (5) and turgor pressure (6). A recent review (14) emphasizes that root growth rates—and presumably root growth pressures—are influenced by mechanical resistance of soil, moisture supply, aeration, temperature, chemical environment, and diseases.

The research reported in this paper was designed to evaluate the relative penetration of the roots of certain legumes when compared to those of cotton and sesame under experimental conditions where mechanical resistance of the soil is the sole limiting factor.

EXPERIMENTAL PROCEDURE

Wax substrates were used to provide nonporous media for the root penetration experiments. Each substrate was prepared by heating a commercially available wax[3] to approximately 20° C. above melting point and pouring a ½-inch layer of wax into a gallon fruit can cut to one-half original height. This wax layer was allowed to harden until temperature equilibrium was reached inside a growth chamber. Nine waxes were used to provide widely different substrate rigidities. American Society of Testing Materials Needle Penetration Test D 1321-57T (1) was used to measure penetrability of the six harder, or more rigid, waxes. Cone Penetration Test D 937-49T was used to measure rigidity of the three softer waxes. These tests measure by 0.1 mm. increments the depth that standard probes will penetrate the waxes under controlled conditions. Since the probe shapes are different, a discontinuity exists in penetration numbers.

Amarillo fine sandy loam, collected from the 0- to 4-inch layer of a cultivated field near Spade, Texas, was used. Characteristics of this soil are listed in table 1. On each substrate, a ¾-inch layer (300 g.) of loose air dry soil (1.4% moisture content by weight) was spread and the soil surface smoothed. Twenty-five seeds of one of the species were spread evenly on the soil layer in each container. The seeds were then covered with 300 g. of air dry soil and the entire soil mass in each can wetted with 75 ml. of water. After wetting, the soil bulk density was approximately 1.35 g./cm³. To suppress evaporation, each can was covered with clear plastic material held in place by a rubber band.

Plant species used were guar *(Cyamopsis tetragonolobus)*, hairy vetch *(Vicia villosa)*, cowpeas *(Vigna sinensis* var. Chinese Red), sesbania *(Sesbania exaltata)*, mung beans *(Phaseolus aureus)*, cotton *(Gossypium hirsutum* var. Stormmaster), and sesame *(Sesamum indicum)*. Only the six most rigid substrates were used in the root penetration studies of sesame, hairy vetch, and mung beans. All nine substrates were used with guar, sesbania, cotton, and Chinese red cowpeas.

The cans were placed in a growth chamber maintained at 80° ± 1° F. Plant germination and growth periods were 6 days for replicate 1, 7 days for replicate 2, and 6 days for replicate 3. Termination of each test occurred when plant leaves reached the plastic cover on a majority of the cans. After a growth period had ended, soil was washed from the plant roots and from the wax surface. The plant roots that had penetrated each substrate for at least one millimeter were counted. This depth of penetration was selected arbitrarily as a point at which roots had achieved positive penetration. No attempt was made to correlate this depth with zones of maximum sorption of nutrients or water within the root.

On replicate 3, diameters were measured of roots washed from the soil of the hardest wax substrate. None of the roots had penetrated this substrate. Using a micrometer eye-piece on a monocular microscope, size of randomly selected roots was measured at a dis-

[3] Bareco Wax Company, Barnsdall, Oklahoma.

Table 1—Characteristics of 0- to 4-inch cultivated layer of Amarillo fine sandy loam.

Mechanical analysis - sand (greater than 50 microns)	78.0%
silt (50 - 20 microns)	[illegible]
silt (20 - 2 microns)	3.1%
clay (less than 2 microns)	16.2%
Liquid limit	[illegible]
Soil moisture tension values - 1/3 bar	[illegible]
1 bar	[illegible]
5 bars	[illegible]
15 bars	6.0%
Calcium carbonate equivalent	1.4%
Organic matter	1.0%
Cation exchange capacity	[illegible] me/100 g. soil
pH	7.1
Predominant clay minerals	[illegible]

[1] Contribution from Soil and Water Conservation Research Division, ARS, USDA, and the Texas Agricultural Experiment Station cooperating.

[2] Soil Scientists (Physics), Western Soil and Water Management Research Branch, SWCRD, ARS, USDA, Southwestern Great Plains Field Station, Bushland, Tex., and Fort Collins, Colo., respectively.

Table 2—Effect of wax hardness on the ratio of plant roots penetrated to seeds germinated.

Wax type	Pene-tration number	Soy-beans	Mung beans	Sesame	Hairy vetch	Guar	Cotton	Cow-peas
Be Square 175/180		0.64	0.00	0.07	0.08	0.39	0.54	0.64
	19.5*	0.52	0.00	0.10	0.07	0.38	0.57	0.42
		0.50	0.00	0.09	0.01	0.30	0.50	0.49
Cerawax Amberwax		1.58	0.93	0.68	1.13	0.82	0.89	0.60
	25.0*	1.00	1.20	1.12	1.16	0.91	0.96	1.30
		0.86	0.92	0.65	1.34	0.82	0.90	0.83
Victory 155 Amberwax		1.15	0.84	1.00	1.08	2.04	0.83	1.61
	33.0*	1.39	1.03	1.54	1.50	1.71	1.39	1.50
		1.12	1.48	0.45	1.34	1.53	1.22	1.59
ES 2002 # 157		1.60				2.12	1.00	2.10
	31.0†	1.16				1.64	1.14	2.52
		1.54				1.77	1.00	2.48
ES 2012 # 158		1.56				1.59	1.58	2.96
	26.5†	2.02				1.78	1.30	2.64
		2.04				1.57	1.90	1.45
Microseal Amberwax		1.26				1.50	1.65	2.00
	35.0†	1.72				2.01	1.05	2.44
		1.48				2.36	1.85	2.18

* ASTM Needle Penetration Test D-1321-57T † ASTM Cone Penetration Test D-937-48T

tance of one millimeter from the tip. In addition, the variation in root diameter with distance from the tip was measured on a root selected to indicate characteristic shape of the root tips of each species.

RESULTS AND DISCUSSION

To penetrate a medium with pores smaller than the critical diameter of the root tip, roots must exert force sufficient to move material from their paths. The force required to penetrate the medium varies with the hardness—or rigidity—of the substrate. The relative production of roots which can exert sufficient force to penetrate various media is illustrated in table 2. The ratios between the roots which penetrate the wax surface one millimeter or greater distance and the number of seeds which germinated are presented in order to correct for differences in germination.

When the ASTM wax penetration number was 15.5 or less—the lower the penetration number the more rigid the wax—no roots from any species penetrated the substrate surface to a depth of 1 millimeter. Because the wax penetration numbers were less than 15.5, data are not presented for the 3 most rigid wax substrates. However, when the wax penetration number was 19.5, some roots of all except one species penetrated the substrate in one or more replications. No roots of mung beans could exert sufficient force to penetrate the substrate with a ASTM needle penetration number 19.5. When the needle wax penetration number was 25.0, an average of almost 1 root from each mung bean seedling could penetrate. Mung beans, a legume, seemed to be the least effective species in exerting the minimum force necessary for some of the roots to penetrate a nonporous substrate.

Due to genetic variability of the plants and variation in micro-environment of each root, the ability of any one type of plant root to penetrate a substrate should vary according to a presumably normal distribution pattern. As substrate rigidity decreases, a rigidity range should be reached where only a few root tips can penetrate. With further rigidity decreases, the percentage of roots with ability to penetrate should increase until most of the roots contacting the wax surface should penetrate the substrate. This increasing root penetration trend with decreasing wax hardness is apparent with each of the seven species.

Some of the roots of each species grew through the wax layers to depths of greater than one centimeter. The average depth of penetration seemed greatest in the softest substrates, but the total depths of penetration were not quantitatively evaluated.

Table 3—Size of roots 1 millimeter from the tip of 7 plant species.

	No. roots measured	Size in mm. Range	Average
Soybeans	16	.21 - .44	.32
Mung beans	17	.31 - .60	.46
Sesame	15	.15 - .26	.22
Hairy vetch	15	.19 - .48	.33
Guar	17	.20 - .50	.34
Cotton - primary	10	.26 - .79	.41
lateral	9	.30 - .43	.33
Chinese red - primary	6	.26 - .60	.42
cowpeas - lateral	7	.15 - .31	.22

Table 4—Variation in root size of 7 plant species as a function of distance from the root tip.

Distance from tip, mm.	Root size, mm. Soy-beans	Mung beans	Sesame	Hairy vetch	Guar	Cotton Prim.*	Cotton Lat.*	Cowpeas Prim.	Cowpeas Lat.
1	.32	.33	.30	.40	.37	.28	.26	.40	.16
2	.40	.35	.35	.48	.36	.40	.40	.47	.33
3	.44	.37	.30	.48	.40	.48	.42	.60	.19
4	.44	.31	.38	.48	.40	.38	.48	.70	.36
5	.44	.37	.31	.48	.40	.70	.43	.66	.38
6	.44	.37	.31	.48	.55	.83	.42	.46	.34
7	.44	.37	.31	.46	.40	.85	.42	.60	.31
8	.44	.47	.31	.40	.40	-	.42	.66	.34
9	.44	.40	.31	.48	.40	-	.45	.60	.34
10	.44	.40	.31	.48	.40	-	.46	.66	.34

* Prim. = primary; Lat. = lateral.

In a rigid soil system, Wiersum (15) has concluded that young roots pass through only pores of a size exceeding the diameter of a root tip. If it is assumed that this conclusion is valid for the type of plants used in this experiment, root diameter measurements provide a method of determining root penetration into a rigid soil.

Data indicating the size of roots at a distance of one millimeter are presented in table 3. Although the measured diameter of the smallest root tip did not vary greatly between species, there was a wide difference between species in the diameter of the largest root tip. A large difference also existed in the average size of the root tips. As an example, the range in size of the sesame root tips was from 0.15 to 0.26 mm. with an average of 0.22 mm., but the range in size of the tips of the primary cotton roots was from 0.26 to 0.79 mm. with an average of 0.41 mm. In soils where pores are well graded in size, there are more pore spaces that are larger than 0.22 mm. than that are larger than 0.41 mm. In a rigid soil with pores well graded in size, the size of the root tips make it more likely that a sesame root would grow into and through a compact layer than that a cotton root would grow through the same layer. However, no trend between legumes and nonlegumes in size of root tips was apparent.

Portions of a root tip can be classified as the root cap, and the zones of meristematic activity, elongation, and maturation. When the root system is expanding, cells of the zone of elongation tend to force all cells nearer the root tip through the soil mass. This zone of elongation commonly ends at about 1 cm. from the tip.

It seems possible that growth of cells in the meristematic and elongation zones may cause root tips to become wedged into voids smaller than the critical diameter of the root. Because of this possibility of wedging and Wiersum's (15) conclusion that roots cannot pass through a narrow pore by means of a short constricted zone, the variation in size with distance from the tip would influence root penetration into and through a small pore. Table 4 presents data indicating the size of the terminal centimeter of one or more roots of each species as a function of distance from the tip. The shape of this portion of the primary cotton root is different from the shapes of the other plant root tips or even the lateral roots of cotton. Diameter of the primary cotton root tip continually increased with distance from the tip, but the root diameters of the other species, and the lateral roots of cotton, did not increase to any great extent at a distance greater than 2 or 3 mm. from the tip.

When the plants were grown under the same environmental conditions, no large difference between the ability of a legume and a nonlegume root to create its path was apparent. Legumes did not always have a greater tendency than nonlegumes toward profuse branching. Legume roots did not necessarily vary from those of nonlegumes in size of the terminal one centimeter of the root. Therefore, under these experimental conditions, legumes probably would not be more effective than nonlegumes in penetrating compacted zones of one centimeter thickness. It should be emphasized, however, that neither the ultimate size nor the relative longevity of the root channels was investigated. A marked difference in one of these two factors may determine relative effectiveness of legumes versus nonlegumes in soil physical condition improvement.

SUMMARY

In laboratory studies, the penetrating abilities of legume roots were compared with the ability of cotton and sesame. Waxes provided nonporous substrates of different rigidity. Root diameter measurements were used to evaluate effects of soil porosity. Root penetrating abilities varied with the species of plant, but those of legumes were not significantly greater than nonlegumes.

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A Graphical "Regression Selection" Technique for Maturity-Related Characters in Field Corn[1]

G. W. Gorsline[2]

SYNOPSIS. A graphical "regression selection" technique for grain yield as related to maturity is described and illustrated. It is shown that more appropriate positive and negative selection results from its use than when maturity is not adequately considered.

SELECTION criteria must necessarily remain somewhat subjective. Various methods of constructing selection indices have been devised. In all such indices, specific characters are given more or less subjective values. It is probable that no two breeders, based on experience and local studies, would completely agree on appropriate selection criteria or on assigning relative values.

Any sequential selection scheme, such as is commonly used, demands unbiased estimates of the character in question. Certain maize characters of economic importance are correlated with maturity measures; among these is grain yield. Unconfounded evaluation of such characters demands that the direct effects of maturity be removed. A graphical method of selection in relation to maturity is presented for which the term "regression selection" is proposed.

LITERATURE REVIEW

Many investigators have recognized the general positive correlation of maize grain yield and maturity (3, 4, 6, 7, 8, 9, 10), although adverse growing conditions are reported as effectively masking the normal trend in some instances (1, 6).

Numerous measures of maize maturity have been reported, including (2, 3, 5, 6, 7, 8, 9): *(a)* maximum kernel dry matter accumulation, *(b)* silking date, *(c)* tassel emergence date, *(d)* bleached or dead husks, *(e)* grain moisture at harvest, and *(f)* grain test weight. Interactions between the various measures of maturity have been pointed out (2, 5, 7, 8, 9).

Stringfield et al. (7) presented a graphical method of corn hybrid grain yield evaluation in which a scattergram

[1] Authorized for publication on January 21, 1960 as paper number 2428 of the journal series of the Pennsylvania Agricultural Experiment Station.

[2] Assistant Professor of Agronomy, The Pennsylvania State University, University Park, Pennsylvania.

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PENETRATION OF COTTON SEEDLING TAPROOTS AS INFLUENCED BY BULK DENSITY, MOISTURE CONTENT, AND STRENGTH OF SOIL

HOWARD M. TAYLOR and HERBERT R. GARDNER

United States Department of Agriculture[1]

Received for publication December 4, 1962

Three of the most frequently published explanations for poor root growth in compacted zones are: (*a*) aeration was inadequate within or below the compact zone (1, 3, 6); (*b*) soil pores were too small within the compact zone for root caps to enter (4, 12); and (*c*) some critical soil bulk density was exceeded (9, 10, 11).

Adequate aeration is available in compacted fine sandy loam soils of the Southern Great Plains. Plant roots can even enter a nonporous substrate if the substrate is not too rigid (8). The third possibility—that of a critical soil bulk density—cannot adequately explain the effects of tillage or pressure pans upon rooting habits of plants. The apparent critical bulk density—at which no roots grew through the soil mass—was lower in years when substantial drought periods occurred than during years when soil moisture was available [(footnote[2] and (7)]. This phenomenon suggested that the magnitude of soil bulk density effects upon root penetration depended upon the soil moisture content.

In the present laboratory investigation, validities of the critical bulk density concept and an alternative soil strength hypothesis were evaluated under conditions where soil aeration was not limiting root penetration.

[1] Soil and Water Conservation Research Division, Agricultural Research Service, Southern Plains Branch, Southwestern Great Plains Field Station, Bushland, Texas (senior author), and Northern Plains Branch, Fort Collins, Colorado (junior author).

[2] H. M. Taylor, E. Burnett, and N. H. Welch. Influence of soil strength on root growth habits of plants. Paper presented at the 1962 annual meeting of the American Society of Agricultural Engineers.

PROCEDURE

Cotton plants were grown in cylinder assemblies consisting of two steel cylinders with inside diameter of 4.02 cm. The bottom cylinder was 2.54 cm. long and the upper one 5.08 cm. These two cylinders were held together rigidly with a steel hose clamp. The cylinder assembly was placed on a wetted porous plate of a pressure plate apparatus (5). Oven-dry Amarillo fine sandy loam soil in sufficient quantity to provide the desired compressed bulk density was weighed to the nearest 0.01 g. and poured into the cylinder assembly. The soil was soaked overnight and then brought to ⅓ bar soil moisture tension at 80° ± 2°F. When moisture equilibrium was achieved, the cylinder assembly was placed in a laboratory press, a piston was inserted in the cylinder, and all the soil was compressed into the bottom 2.54 cm. of the cylinder assembly. The cylinder containing the compressed soil was returned to the pressure plate apparatus. The soil was again soaked overnight and then brought to moisture equilibrium at the desired soil moisture tension.

After water outflow from the pressure plate had ceased, five seeds of cotton (*Gossypium hirstum* var Stormmaster) were placed on the surface of the compacted soil in a cylinder assembly. A 2.5-cm. layer of Amarillo fine sandy loam soil, equilibrated to the same soil moisture tension as the compressed soil beneath the seeds, was used as cover soil. To provide similar plant reaction pressures, the cover soil was firmed by a 6.2×10^6 dynes cm.$^{-2}$ stress on the soil surface.

Sixteen compressed cores of each bulk density and soil moisture tension were planted. Soil moisture tensions of ⅙, ⅓, ½, and ⅔ bars and with bulk densities of 1.55, 1.65, 1.75, 1.80, and 1.85

g.cm.$^{-3}$ were used. With a limited number of samples a 2-bar tension treatment was used in addition.

Twenty assemblies containing compressed soil were placed in a 30-cm.-diameter, 20-cm.-high, rigid black plastic tube sealed to a clear acrylic plastic base plate. A covering sheet of clear plastic film was held in place by strong rubber bands. The purpose of this small plastic container was to control evaporation of moisture from the compressed soil cores. The container was placed in a continuously lighted room maintained at 80° ± 2°F. for a 12-day germination and growth period. The taproots that penetrated through the 1-inch compressed soil were recorded daily by visual inspection of individual cylinder assemblies.

At the end of the growth period, soil moisture percentages and taproots that penetrated through the 1-inch cores were determined. Strengths of the upper surface were determined using a force gauge[3] as a static penetrometer. The penetrometer stress was calculated from the maximum force required for the 0.48-cm.-diameter cylindrical penetrometer tip to be forced 0.5 cm. into the soil surface.

Four control samples of soil at each bulk density and soil moisture tension, identical in other respects to the planted assemblies but containing no cotton seeds, were subjected to the same procedure. The mean soil strengths and moisture contents were used to define the initial conditions in the compressed cores.

To correct for variations in germination, a root penetration percentage was calculated:

$$\text{root penetration percentage} = \frac{\text{taproots penetrating the entire depth} \times 100}{\text{seeds germinated}}$$

RESULTS AND DISCUSSION

Many research workers have reported that a decrease in root penetration was associated with an increase in soil bulk density. Results of this experiment (fig. 1) show the same general trend. The data do not support the concept that any one critical bulk density exists for this soil, but

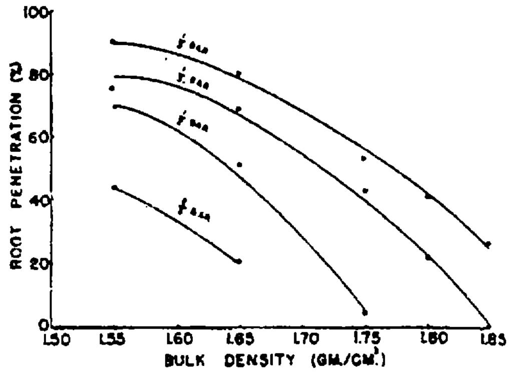

FIG. 1. Root penetration of Amarillo fine sandy loam soil as affected by soil bulk density and soil moisture tension. Each point represents 80 planted seeds.

they confirm that the bulk density at which no roots penetrate Amarillo fine sandy loam depends upon the soil moisture content.

In figure 1, smoothed curves drawn through the average root penetration percentages are used to indicate the effects of soil moisture tension on the bulk-density–root-penetration relationship. At a bulk density of 1.65 g.cm.$^{-3}$, about 80 per cent of the taproots penetrated the soil cores at ⅙-bar tension, but only 20 per cent penetrated at ⅔-bar tension. The soil moisture content by weight—averaged for all bulk densities—was 8.0 per cent at ⅙-bar soil moisture tension, and 7.3 per cent at ⅓-bar, 6.1 per cent at ½-bar, and 5.5 per cent at ⅔-bar tensions. Thus, at a bulk density of 1.65 g.cm.$^{-3}$, a loss of 2.5 per cent moisture by weight caused a 60 per cent difference in root penetration. When the bulk density was 1.75 g.cm.$^{-3}$, a moisture loss of 2.5 per cent caused a change in root penetration from 60 to 0 per cent. At a given bulk density, taproots had a greater probability of penetrating the lower than of penetrating the higher soil moisture tension cores.

A significant positive relationship ($r = +0.48$) existed between root penetration and soil moisture content. The fact that an increase in moisture content caused an increase in root penetration precludes aeration of the soil within the cores from being the factor limiting root penetration. If aeration were limiting, an increase in soil moisture would cause a decrease—not an increase—in root penetration.

Since aeration was not the factor causing failure of the critical bulk density concept, an alternative cause must be found. A force balance at

[3] Model 719-40, John Chatillon & Sons, 85 Cliff St., New York. Product and company name is included for the benefit of the reader and does not infer any endorsement or preferential treatment by the U. S. Department of Agriculture of the product listed.

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root anchorage, and (c) those
of the soil.

Soil strength—as measure
penetrometer—increased as t
the soil moisture tension incre
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The deviation for a specific det
exceeded 10 per cent of the a

There was a highly signific
tion ($r = -0.96$) between th
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An increase in soil strength
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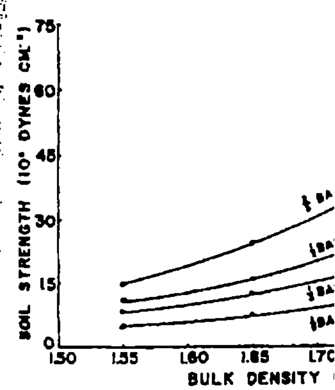

FIG. 2. Effect of bulk dens
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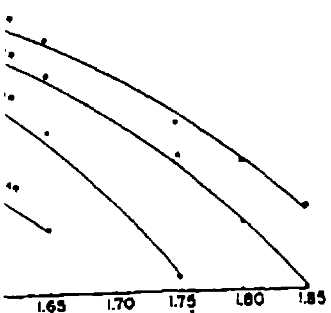

netration of Amarillo fine sandy
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tension, but only 20 per cent
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er cent at ⅓-bar soil moisture
per cent at ½-bar, 6.1 per cent
5.5 per cent at ⅔-bar tensions.
density of 1.65 g.cm.$^{-3}$, a loss of
isture by weight caused a 60 per
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as 1.75 g.cm.$^{-3}$, a moisture loss of
used a change in root penetration
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greater probability of penetrating
n of penetrating the higher soil
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positive relationship ($r = +0.48$)
n root penetration and soil mois-
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the zone of cell division within the plant root suggests such a cause.

To penetrate a soil mass, a plant root must exert a root growth pressure greater than the resistance of the soil through which it is growing. Pfeffer (2) and Gill and Miller (3) have emphasized that conditions affecting plant vigor will alter the root growth pressure of a plant. Taylor and Gardner (8) have shown that adequate anchorage is necessary before a root can transmit its maximum root growth pressure to the resisting soil mass. Root penetration, therefore, is influenced by three classes of variables: (*a*) those affecting root growth pressure, (*b*) those affecting root anchorage, and (*c*) those affecting strength of the soil.

Soil strength—as measured by the static penetrometer—increased as the bulk density or the soil moisture tension increased (fig. 2). Only the average soil strength for a particular soil moisture tension and bulk density is presented. The deviation for a specific determination seldom exceeded 10 per cent of the average strength.

There was a highly significant linear correlation ($r = -0.96$) between the soil strength and the root penetration percentage (fig. 3). About 70 per cent of the taproots penetrated soil with a strength of 10×10^6 dynes/cm.^{2}, but only 30 per cent penetrated when the strength was 20×10^6 dynes/cm^2. A closer relationship existed between soil strength and root penetration than existed between soil bulk density and root penetration ($r = -0.59$) or between soil moisture content and root penetration ($r = +0.48$).

An increase in soil strength not only reduced the percentage of roots penetrating the soil but

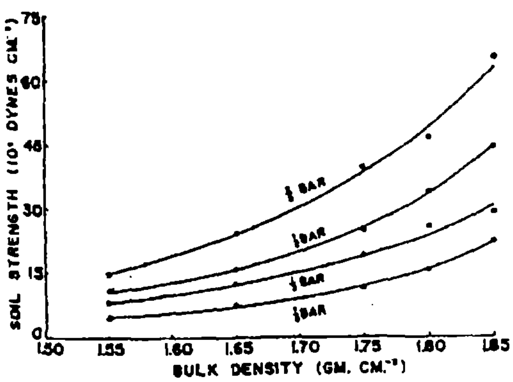

FIG. 2. Effect of bulk density and moisture tension of Amarillo fine sandy loam soil on soil strength as measured by a static penetrometer.

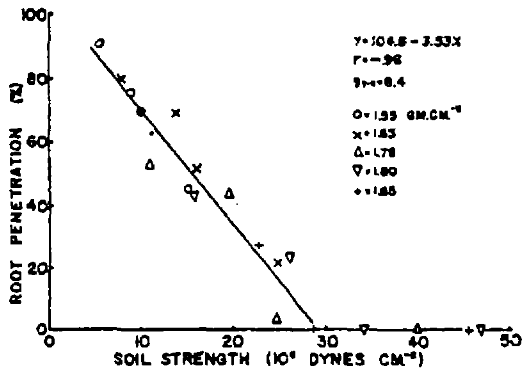

FIG. 3. Root penetration of Amarillo fine sandy loam soil as influenced by soil strength. Each point represents 80 planted seeds.

TABLE 1

Percentage of cotton taproots that had penetrated at time (t), *as compared with those that penetrated at 11 days* (*cores equilibrated at ⅓-bar soil moisture tension*)

Bulk Density	Soil Strength	Penetration of Taproots						
		3 days	4 days	5 days	6 days	7 days	8 days	9 days
g./cm³	*10⁶ Dynes/cm.²*	%						
1.55	9.0	60	85	92	98	98	100	100
1.65	13.1	50	74	90	92	92	100	100
1.75	19.3	6	44	69	72	84	100	100
1.80	23.4	0	0	43	64	71	93	100
1.85	29.0	No penetration of roots						

also decreased the rate at which the roots grew through the soil (table 1). An average root growing through 2.54 cm. of soil with a strength of 23.4×10^6 dynes cm.$^{-2}$ (equivalent to 340 psi) required 2 more days to penetrate the soil than one growing through soil at the same soil moisture tension but with a strength of 13.1×10^6 dynes cm.$^{-2}$

In contrast to the present conclusion that the critical bulk density concept is not valid under conditions where soil moisture loss occurs, there was a soil strength (29.6×10^6 dynes cm.$^{-2}$) above which no roots penetrated. This 29.6×10^6 dynes cm.$^{-2}$ limit was valid whether the high strength was caused by an increased bulk density or by a decreased soil moisture content. Root penetration, however, is a function not only of soil strength but also of soil porosity—size, continuity, and tortuosity of voids within the soil. The soil strength concept may be valid only when voids provide few or no avenues for roots to penetrate a high strength soil mass.

If any factors caused by the differential treatments limit the ability of plant roots to exert their characteristic root growth pressure, more than one regression line will be required to adequately represent the soil-strength–root-penetration data. As an example, assume that soil aeration was limiting root growth pressures in some cores at the ⅓-bar soil moisture tension but was not limiting root growth pressures at the ⅓-, ½-, and ⅔-bar tensions. Under these conditions, one regression line would have adequately represented the soil-strength–root-penetration data for the ⅔-, ½-, and ⅓-bar tensions, but a regression line predicting lower root penetration percentages at a particular soil strength probably would have been required for the ⅓-bar tension data.

It was concluded that neither soil aeration nor soil moisture tension caused differential root growth pressures within the ⅓- to ⅔-bar soil moisture tension range. The results of the 2-bar soil moisture tension trial, however, showed that those cotton roots were much less likely to penetrate at a particular soil strength. It was concluded that the 2-bar tension had reduced root growth pressures below those at ⅔-bar tension.

Certain precautions are necessary in extrapolating these data. There is no assurance that the cotton seedlings exerted their maximum root growth pressure nor that firming the cover soil actually caused a maximum anchorage for the developing taproot. In addition, a different penetrometer tip or a different method of measuring soil strength would result in different magnitudes of soil strength for a given rooting percentage.

The fact remains, however, that soil strength at the time root penetration occurred—not soil bulk density—was the critical impedance factor controlling root penetration through the soil cores.

SUMMARY

Effects of soil bulk density, moisture content, and soil strength on penetration of cotton seedling taproots were evaluated, using soil cores compressed to 5 different bulk densities and 4 different soil moisture tensions. A correlation coefficient of −0.96 was obtained for the relationship between soil strength (as measured with a penetrometer) and taproot penetration. Although the moisture-content–root-penetration and bulk-density–root penetration relationships were significant, the correlation was much less than that for soil-strength–root-penetration. It was concluded that soil strength—not soil bulk density—was the critical impedance factor controlling root penetration in the sandy soils of the Southern Great Plains.

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IDENTIFICATION OF

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ROOT ELONGATION RATES OF COTTON AND PEANUTS AS A FUNCTION OF SOIL STRENGTH AND SOIL WATER CONTENT

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The data of Peters (3) clearly illustrate that both soil water content and soil matric suction affect root elongation rates. At a soil suction of 1/3 bar and a bulk density of 1.25 g. cm^{-3}, corn roots elongated faster in a soil mixture with a gravimetric water content of 27% than in one with a water content of 8%. At equal water contents, root elongation rates for either a 24- or 48-hour period were greater at a soil suction of 1/3 bar than at a suction of 1.75 bars. Oven-dry weight of root material also increased as suction decreased or as water content increased.

Even when other parts of the root system are adequately supplied with water, soil suction around the elongation region affects dry weight of corn roots (2). However, magnitudes of the soil suction effects on root growth vary with the soil texture (4). Dry weights of adventitious sunflower roots that developed in soil cores were not affected by soil suctions between 0.3 and 1.1 bars in a fine sandy loam soil, but root weights decreased as soil suctions increased from 0.3 to 1.5 bars in a clay loam soil.

Both Peters (3) and Stevenson and Boersma (4) stated that soil compaction may have affected their results. In addition, they controlled bulk density of their test soil material either by controlling the mass of soil per unit volume (3) or by tamping with a spatula (4).

When compared at equal soil strengths rather than equal bulk densities, an increase in soil suction from 0.2 to 0.7 bar did not affect the growth of cotton roots into or through 2.5-cm.-thick cores (5). However, increases in soil suction caused large increases in strength of compacted soil cores, which reduced root penetration and elongation rate.

Barley *et al.* (1) found that increasing the soil suction from 0.3 to 0.7 bar made no difference in the time required for pea and wheat roots to penetrate layers of loose soil, but root elongation rate was reduced by the higher suction in compressed layers. Elongation rates of cotton roots grown in loose soil also were not affected by increases in soil suction from 0.2 to 0.7 bar, but when roots were grown in soil that had been slurried, then dewatered, increases in soil suction decreased root elongation rates (6).

Thus, the literature shows that increases in soil suction within the commonly accepted plant available range sometimes, but not always, decrease root elongation rates of plants. However, part or all of that decrease may actually be caused by an increase in soil strength rather than by an effect of soil suction *per se* on root growth.

This investigation determined the effects of soil water content and soil strength on cotton and peanut root length as a function of time.

PROCEDURE

Root observation chambers were constructed from acrylic plastic material. Each of the three chambers contained four compartments arranged side to side. Dividers were grooved so that a 0.60-cm.-thick, plate-glass sheet formed the front of a compartment that was 5 cm. from front to rear, 15 cm. from side to side, and 45 cm. high.

Bulk samples of fertilized Chesterfield loamy sand (pH 6.2) surface soil were screened through a 2-mm. sieve and oven dried. Subsamples were wetted to 7.4, 5.0, and 4.0 per cent water content by weight for the cotton experiment, and 7.0, 5.5, and 3.8 per cent water

[1] Joint contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, USDA, and the Alabama Agricultural Experiment Station, Auburn University, Auburn, Alabama. Junior author was formerly Instructor of Soils, Auburn University.

for the peanut experiment. These water contents corresponded to 0.17-, 0.75-, and 7.0-bars soil matric suction for the cotton experiment, and 0.19, 0.42, and 12.5 bars for the peanut experiment. Within the range of bulk densities and water contents used in these experiments, soil compactness changes did not alter the water characteristic curve. The wetted soil was stored at least 24 hours in plastic bags.

With the aid of a thin board repeatedly forced downward at the rear of a compartment, the wetted soil was compacted in a chamber placed on a vibrating table. Soil strength was checked periodically with an indentation penetrometer (5, 6) until the soil was compacted to the desired soil strength range. At that point a 4-cm. layer of loose Chesterfield soil was added to provide a seedbed. The cover soil was wetted to the same water content as the compacted soil, but 0.01 per cent by weight of a 1:5 Ceresan-Demosan[2] fungicide mixture had been added to the water used to wet the surface soil.

When the compaction process was completed for the four compartments of an observation chamber, the chamber was transferred to a force loading platform which pushed a penetrometer through the soil at the rate of 4 mm. minute^{-1}. Two force depth traces were made in each compartment.

The penetrometer was a polished steel drill rod 0.318 cm. in diameter and 30 cm. long. The tip of the rod was ground to form a 60° cone. There was no coating on the steel surface nor was the shaft recessed behind the tip.

The soil resistance was sensed by an unbonded strain gage load cell and recorded on a strip chart recorder (Model UL-4), Statham Instruments, Inc., load cell and Type R Dynograph and Type 504D Recorder, Offner Division, Beckman Instruments, Inc.).[2] Penetrometer resistance was calculated by averaging the force values obtained from the strip charts at intervals representing 1-cm.-depth increments of soil to the deepest point of root penetration in the compartment. This averaged force value was divided by the 7.94-mm.^{2} area of the shaft. The measured values of force increased as the penetrometer tip was pushed through the first 1.0 to 1.5 cm. of compacted soil but then did not further increase. This initial portion of each trace was not included during calculation of penetrometer resistance. Skin friction along the sides of the shaft apparently was very low since the force depth traces did not increase in force below the 1.5-cm. depth.

Cottonseed (*Gossypium hirsutum* L. 'Empire') were pregerminated by soaking for 1 minute in 80°C tapwater and then soaking for 8 hours in 27°C tapwater. At that time plants were selected for uniform radicle emergence and planted eight to the compartment. The seed were planted along the glass-soil interface with the radicle tip about 1 cm. above the compacted soil. The loose soil above the seed was firmed by hand to provide reaction force when the radicle encountered the compacted soil.

Peanut seed (*Arachis hypogaea* L. 'Virginia Bunch') were pregerminated in Chesterfield loamy sand at 7.0 per cent by weight water content. The water used to wet the soil contained 0.01 per cent by weight of a 1:5 mixture of Ceresan and Demosan. After 32 hours peanut plants were selected for radicle lengths of 1.0 to 1.5 cm. and transplanted eight to the compartment, with the seed 2 cm. above the compacted layer. The soil was firmed by hand around the seed and radicle to provide reaction force when the radicle encountered the compacted soil.

After planting the cotton or peanut seed, a plastic film was taped over the top of each compartment to eliminate water loss. The root observation chambers were inclined 15° from the vertical so the developing taproots would follow the glass front. Periodic length measurements were recorded for each taproot.

During the entire 110-hour growth period the chambers were maintained in a growth chamber with a 16–8 hour light-dark cycle at 32° ± 1°C. Except during actual root measurements, the glass fronts were covered to exclude light from the peanut roots. Previous experiments (R. W. Pearson, *unpublished data*) had shown that cotton taproots are insensitive to light under these experimental conditions so the cotton root systems were not covered. After 110 hours the compartments were emptied and bulk density was determined for the packed

[2] Mention of a trademark name or a proprietary product does not constitute a guarantee or warranty of the product by the U. S. Department of Agriculture and does not imply approval of the product to the exclusion of others which may also be suitable.

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RESULTS

Cotton taproot lengths as a fu
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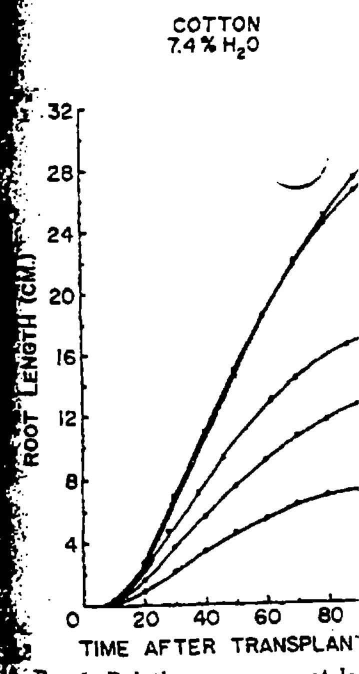

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RESULTS

Cotton taproot lengths as a function of time and penetrometer resistance are presented in figs. 1, 2, and 3 for the 7.4, 5.0, and 4.0 per cent water contents, respectively. The cotton taproots entered the compacted layer about 10, 11, and 13 hours after transplanting for the 7.4, 5.0, and 4.0 per cent water contents, respectively. The data were not definitive, but the possibility exists that entrance of the taproots into the compacted layer was retarded by strength of the compacted layer.

Once the cotton taproots entered the compacted layer, the root length at any particular time varied inversely with the resistance encountered by the roots. The roots elongated fastest at low resistances, and with one exception: any increase in resistance decreased the root length at 110 hours after transplanting.

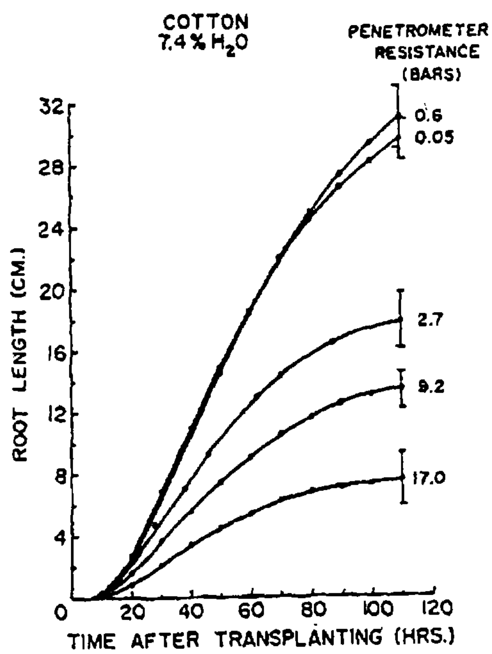

FIG. 1. Relations among root length, time, and penetrometer resistance for cotton grown at 7.4 per cent water content. The vertical lines around the means at 110 hours represent 95 per cent confidence intervals for the means.

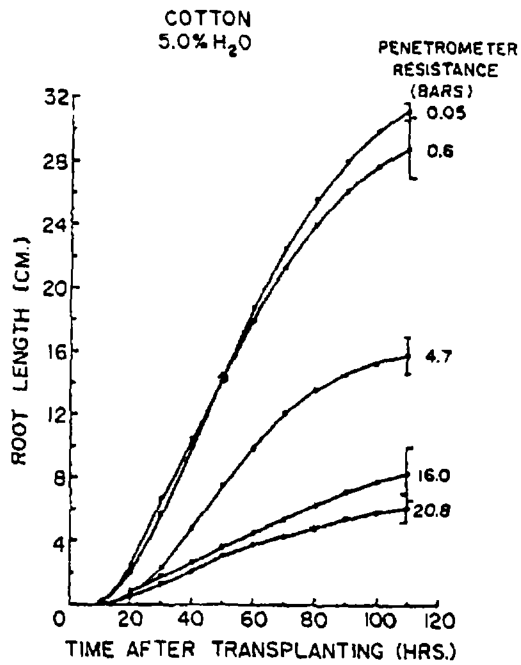

FIG. 2. Relations among root length, time, and penetrometer resistance for cotton grown at 5.0 per cent water content. The vertical lines around the means at 110 hours represent 95 per cent confidence intervals for the means.

At 7.4 per cent water content the average root length was 31.2 cm. while growing through 0.6-bar-strength material but was 29.7 cm. in loose soil. However, these two means were not significantly different at the 95 per cent probability level.

At any particular penetrometer resistance there was no effect of water content *per se* on cotton root elongation within the compacted layer. Figure 4 presents the average elongation rate for the period 40 to 80 hours after transplanting as a function of penetrometer resistance and soil water content. Elongation rate calculations for other time periods showed similar trends.

Peanut root lengths as a function of time after transplanting and of penetrometer resistance are presented in figs. 5, 6, and 7 for the 7.0, 5.5, and 3.8 per cent water contents, respectively. The time required for the peanut roots to enter the compacted layer seemed to be slightly increased by a decreased water content in the loose soil layer, but the data were not definitive.

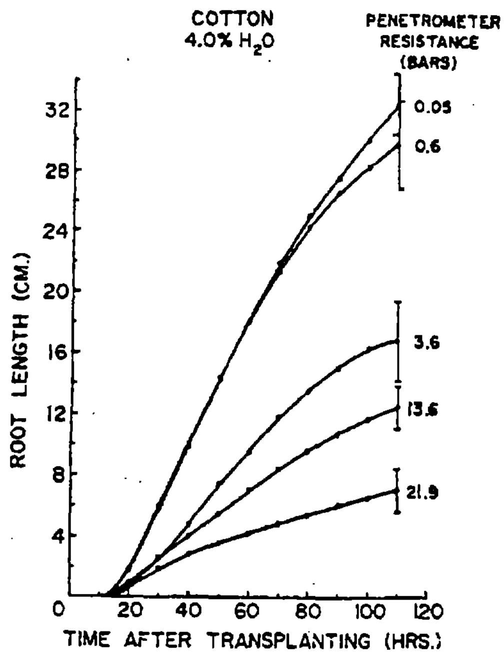

FIG. 3. Relations among root length, time, and penetrometer resistance for cotton grown at 4.0 per cent water content. The vertical lines around the means at 110 hours represent 95 per cent confidence intervals for the means.

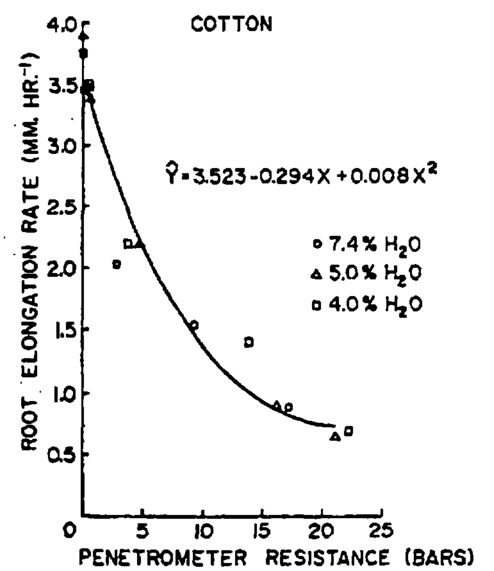

FIG. 4. Effect of penetrometer resistance and soil water content on cotton root elongation for the period 40 to 80 hours after transplanting.

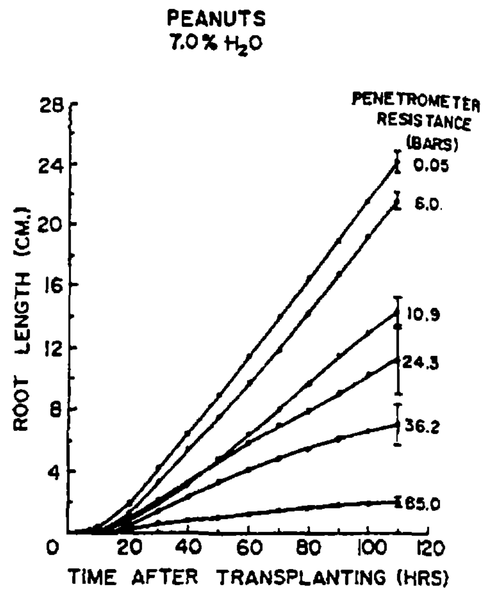

FIG. 5. Relations among root length, time, and penetrometer resistance for peanuts grown at 7.0 per cent water content. The vertical lines around the means at 110 hours represent 95 per cent confidence intervals for the means.

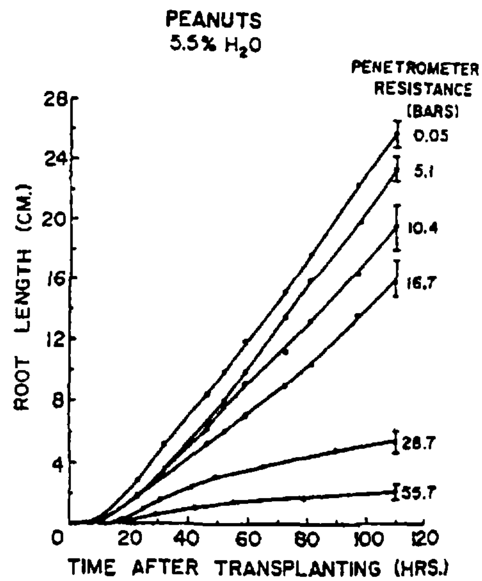

FIG. 6. Relations among root length, time, and penetrometer resistance for peanuts grown at 5.5 per cent water content. The vertical lines around the means at 110 hours represent 95 per cent confidence intervals for the means.

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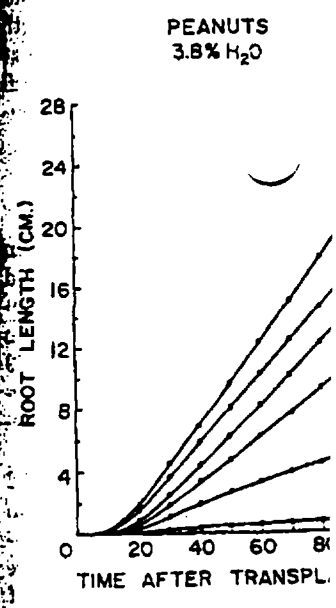

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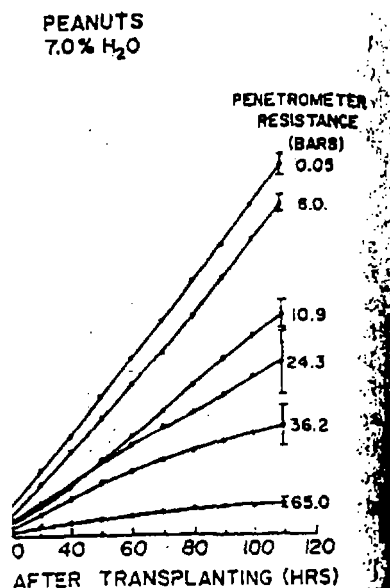

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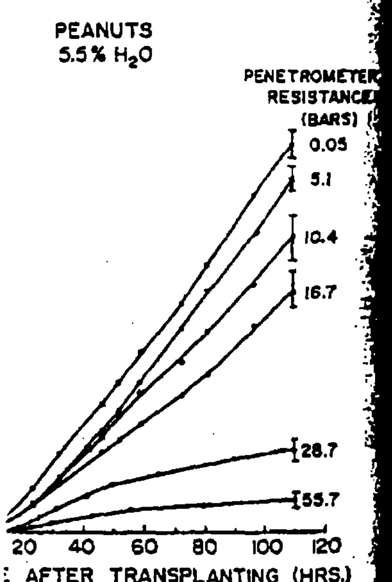

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Peanut root lengths at any time after the roots entered the compacted layers varied inversely with the resistance the roots encountered. At 110 hours after transplanting, lengths of the roots growing through loose soil were 24.1, 25.7, and 26.2 cm. for the 7.0, 5.5, and 3.8 per cent water contents, respectively. Even at penetrometer resistances that exceeded 60 bars (fig. 5 and 7), the peanut roots grew 1 to 2 cm. into the compacted layer during the 110-hour growth period.

Water content *per se* did not affect the relationship between peanut root elongation rate and penetrometer resistance (fig. 8). For the period 40 to 80 hours after transplanting, the roots elongated at the rate of 2.5 to 2.7 mm. hour^{-1} in loose soil but decreased as penetrometer resistance increased until at 60-bars penetrometer resistance the elongation rate was 0.15 mm. hour^{-1}. Elongation rate calculations for other time periods showed similar trends.

The wet weight and height of plant tops were significantly affected by soil water content even where the plant roots were not restricted by high-strength soil (table 1). At the lowest

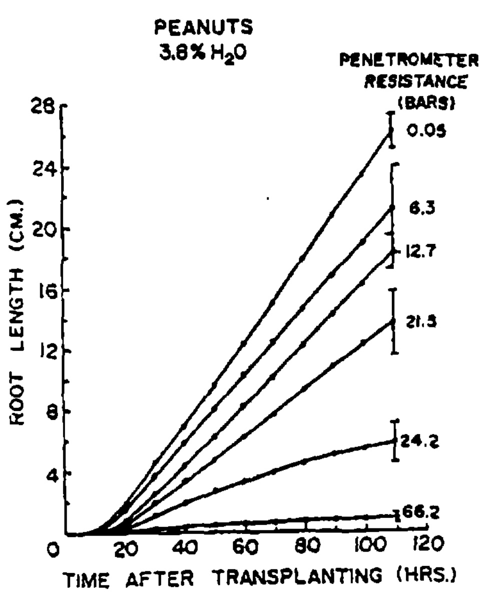

FIG. 7. Relations among root length, time, and penetrometer resistance for peanuts grown at 3.8 per cent water content. The vertical lines around the means at 110 hours represent 95 per cent confidence intervals for the means.

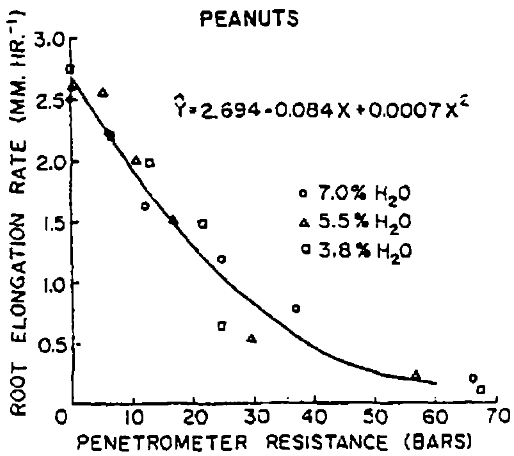

FIG. 8. Effect of penetrometer resistance and soil water content on peanut root elongation for the period 40 to 80 hours after transplanting.

TABLE 1

Effect of soil water content and penetrometer resistance on root length, top length, top wet and dry weights of peanuts and cotton at 110 hours

Water Content	Penetrometer Resistance	Root Length	Top Length	Top Wet Weight	Top Dry Weight
$g.g.^{-1}$	bars	cm.	cm.	g.	g.
		Peanuts			
0.070	0.05	24.5	10.9	2.26	0.34
0.070	29.4	5.9	9.3	2.33	0.36
0.070	65.8	2.0	8.9	2.29	0.32
0.055	0.06	20.3	7.6	1.56	0.32
0.055	29.2	7.5	6.4	1.52	0.36
0.055	72.6	1.2	6.7	1.60	0.30
0.038	0.05	26.0	5.3	1.38	0.34
0.038	20.6	11.7	3.8	1.21	0.28
0.038	60.1	1.4	1.5	0.80	0.32
		Cotton			
0.074	0.05	25.6	9.6	0.61	0.064
0.074	20.5	3.5	10.1	0.57	0.058
0.050	0.05	23.5	8.8	0.47	0.055
0.050	17.8	3.4	9.3	0.48	0.056
0.040	0.05	25.6	8.8	0.41	0.056
0.040	17.4	4.7	6.0	0.35	0.060

soil water content the wet weight of peanut and cotton tops decreased with increased penetrometer resistance, but at the two higher water contents penetrometer resistance did not significantly affect top wet weight of either crop.

TABLE 2

Effect of soil water content and soil bulk dentisy on penetrometer resistance of Chesterfield loamy sand soil

Bulk Density	Penetrometer resistance at water contents of		
	7.4%	5.0%	4.0%
$g.\ cm.^{-3}$	*bars*	*bars*	*bars*
1.10	0.05	0.05	0.05
1.20	1.0	1.3	2.0
1.30	2.5	2.7	4.0
1.40	5.0	6.3	8.0
1.50	9.0	11.5	17.5
1.60	17.5	22.5	36.0

DISCUSSION

Cotton and peanut seedling taproot elongation rates responded to changes in soil strength but did not respond to changes in soil suction between 0.17 and 7.0 bars for cotton, and between 0.19 and 12.5 bars for peanuts. These soil strengths occur at bulk densities that are readily attained either in laboratory or in field experiments (table 2). Therefore, penetrometer resistance or some other soil strength parameter should always be recorded in experiments where short-term root growth measurements are used. Since penetrometer resistance values may be altered by a wide variety of treatments, the experimental results should be analyzed for possible direct effects of soil strength on root growth.

A given incremental increase in penetrometer resistance caused a greater reduction in root elongation rate of cotton than of peanuts. As an example, an increase in penetrometer resistance from 0 to 10 bars reduced cotton elongation rates 62 per cent from the rate at 0 bars, but a similar increase reduced peanut elongation rate only 29 per cent.

The elongation rate necessary for satisfactory establishment will vary with environmental conditions, but a 1.0-cm.-day^{-1} seedling elongation rate may be valid for Alabama conditions. The cotton elongation rate would be less than 1.0 cm. day^{-1} when the penetrometer resistances around the root tip exceeded 27 bars, but peanut plants could maintain that rate until penetrometer resistances exceeded 45 bars.

In research reported here, the penetrometer resistances were measured by pushing a conical-tipped steel rod through the soil mass. In previous experiments (5, 6) the reported values were obtained using an indentation penetrometer that measured the force required to push the tip 1 diameter into the soil surface. The two sets of penetrometer resistance data were experimentally correlated for the Chesterfield soil used in the present research. Penetrometer resistance values by the present technique were 1.33 times those obtained by the indentation technique. The standard error of the estimate was 0.08 for the 1.33 value.

Root volume or fresh root weight as a function of time was less affected than root length by an increase in penetrometer resistance. Actual data are not presented here because of the difficulty of obtaining soil-free roots, but visual observation showed that an increase in penetrometer resistance caused the root diameters of both cotton and peanuts to increase. Although this increased diameter would not appreciably affect seedling establishment, it might affect interpretation of short-term root growth experiments.

Visual observations also showed root diameter increased as soil water content increased, particularly at low soil strengths. Although root elongation rates as functions of soil strength were not affected by soil water content, root volumes or fresh root weights at a low soil strength would have increased as soil water content increased.

SUMMARY AND CONCLUSIONS

In short-term experiments root elongation rates of cotton and peanuts were decreased as soil strengths (measured with a penetrometer) increased. Soil matric suction between 0.17 and 7.0 bars for cotton and between 0.19 and 12.5 bars for peanuts did not affect the relation between root elongation rate and penetrometer resistance.

An increase in penetrometer resistance to 7.2 bars decreased cotton root elongation rate to 50 per cent of maximum, but 19.1-bars penetrometer resistance were required to decrease peanut root elongation rate to 50 per cent of maximum. A substantial peanut root elongation rate occurred at 35-bars penetrometer resistance.

With both cotton and peanuts, top weights and lengths increased as soil matric suction decreased. However, increases in penetrometer

tance reduced top weights at the highest suction.

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Damage to Recently Thinned Loblolly Pine Stands by Hurricane Donna

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Wilfred C. Williams
Thomas C. Nelson

Abstract. Hurricane damage was assessed by determining the percentage of trees injured by the storm. Stand and soil characteristics were determined. Tree damage was recorded separately for "main stem" (breakage) and for "root system" (displacement from original position or blowdown). Over 99 percent of damaged trees were of the second type. Stem breakage was insignificant. Damage was more severe on soils having moderately coarse textured profiles than on soils with finer textured profiles. It was most severe where restrictive layers occurred within the profile that tended to retard root and water penetration.

In recent times tropical hurricanes have struck repeatedly along the Gulf and Atlantic coasts, doing a tremendous damage to timber stands near the coast and less serious damage inland. Although all hurricanes on a grand scale are similar by definition, the kind of damage has varied. Observations indicate that the forest's location in relation to the storm's eye explains some of the variation in damage among stands. Within an individual stand, variation in damage has been correlated (8) with the size of the timber and the exposure of the trees to the wind.

Foresters and soil scientists believe that hurricane damage may also be associated with soil and timber stand characteristics. Hurricane Donna, which passed along the Atlantic coast in September 1960, provided an opportunity for study and the results are summarized in this paper.

The Storm

Tropical Hurricane Donna passed along the Atlantic coast of North Carolina and Virginia on September 11 and 12, 1960. The large eye (possibly the largest on record) was a continuing feature as Donna moved rapidly northeastward paralleling the Middle Atlantic coast during the morning hours of the 12th. A complete description of Hurricane Donna was obtained from the National Weather Records Center of the U. S. Weather Bureau, at Asheville, N. C., and from local observations.

In North Carolina, sustained winds ranged from 53 mph at Wilmington to 83 mph at Elizabeth City. Gusts were measured or estimated in excess of 100 mph along the coast and at 80 to 90 mph along the path of the storm's center. In Virginia, sustained winds reached 80 mph at Cape Henry, and 75 mph at Norfolk, with gusts around 90 mph in the area under study.

Rainfall preceding and during the storm was heavy. For September 11 and 12 at Gatesville, N. C., 6.37 inches were recorded, and 6.17 inches for the same period at Holland, Va. At Como, N. C., 9.00 inches were recorded by the U. S. Forest Service. Heavy rainfall, a feature of this storm, set the stage for the type of damage sustained.

Rainfall pattern was similar at Wilmington, Hatteras, and Norfolk, beginning 19 to 20 hours prior to the storm passage, and with 12 to 22 percent of all rain falling in a 5- to 9-hour period. There followed a 3- to 4-hour period of no rain, and then 75 to 79 percent of the total storm's rain fell in a period of 7 to 11 hours immediately preceding the storm proper. Light rains continued for 2 or 3 hours after the storm had passed. The heaviest rainfall (over 1 inch per hour) occurred 2 to 4 hours prior to the time of maximum wind speeds.

The path of the storm's eye passed to the east of an eight-county area in which damage was studied (Fig. 1). Forest stands included in this survey were distributed from the path of the eye of the storm to a distance of about 60 miles to the northwest.

Methods

Preliminary observations indicated that high winds did heavier damage in thinned stands than in unthinned stands. Therefore, only planted or natural loblolly pine stands that had been thinned during the preceding three years were included in this study. Of the 102 stands sampled, 92 originated from natural regeneration and 10 had been planted. All had been thinned by the Virginia Division of Forestry; the Union Bag-Camp Paper Corporation, Camp Division; or Weyerhaeuser Company, North Carolina Division.

Thinning varied from very light (thinnings from below) to heavy (crown thinnings designed to establish seed production areas). The density of each stand before wind damage was estimated and expressed in percent (7). It ranged from 20 to over 100 percent of full stocking. Most of the stands were between 40 and 70 percent stocked.

Average tree size varied from 6.1 inches d.b.h. in a young plantation to 15.0 inches in a natural stand of large sawtimber trees.

In each stand, tree damage was determined on enough 1/10-acre circular plots of uniform soil to obtain a sample of about 50 trees. In total, 314 of these circular plots were studied, including tallies of 4,796 trees. Each tree was classified as "undamaged," "damaged main stem," or "damaged root system." Damaged main stem referred to trees with broken stems. Dam-

The authors: Williams is soil scientist, Soil Conservation Service, U. S. Dept. Agric., Courtland, Va.; Trousdell and Nelson are on the staff of the Southeastern Forest Expt. Sta., Forest Service, U. S. Dept. Agric., Asheville, N. C. The assistance of P. E. Lemmon, U. S. Dept. Agric. Soil Conservation Service, Washington, D. C., is gratefully acknowledged.

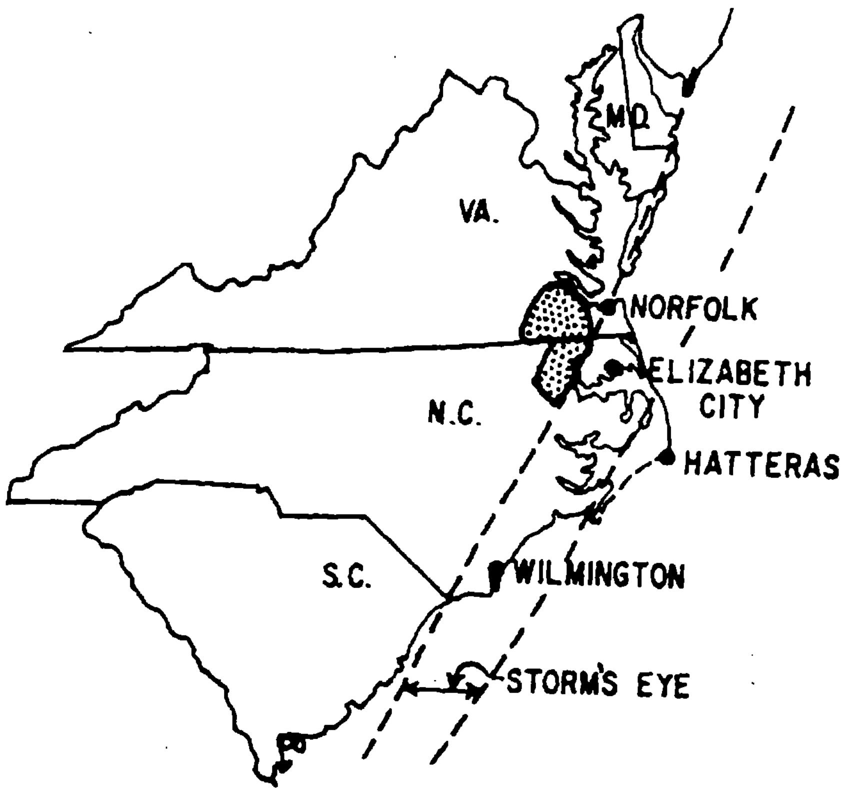

FIG. 1.—Path of tropical Hurricane Donna, showing location of the eight-county study area (shaded). This area extends approximately 60 miles to the northwest of the path of the hurricane.

aged root system included uprooted or leaning trees where roots had been displaced from their original position causing permanent injury. Only root damage is considered in this paper because main stem damage was insignificant (0.3 percent).

Soils on each of the 102 sampled stands were examined, classified, and named according to a national system used by the Soil Conservation Service (*6*). There were not enough samples on any of the named soils so that they could be studied individually. Soils were, therefore, grouped to facilitate study of the possible influences of certain major physical characteristics on wind damage. The first criterion for these groupings was the dominant textural class of the entire soil profile. Three such classes were used — moderately coarse textured profiles, medium textured profiles, and fine textured profiles. Within each of these groups, standard drainage classes were recorded for each soil. Field examinations showed that the soils on 16 of the study areas were not typical for the named series because their profiles showed a nontypical layer of impervious material that acted as a barrier to the taproot and water penetration (Table 1). These layers were generally below the sola[1] and at depths of from 42 to 52 inches. Such layers tend to hold water within the soil layers above, causing "water-logging" or "super-saturation" during periods of heavy rainfall. The extent of such nontypical conditions is not known for the soils in question, but in a detailed soil survey they would be classified as "inclusions," or mapped as "phases," depending upon their continuity and extent.

None of the soil series studied had such restrictive layers in the typical profiles except the Atlee series, which may or may not have a thin restricting layer in the lower solum. However, none of the plots examined on Atlee soils had a layer that was classed as restrictive.

Wind damage may be related to many factors, among which are the characteristics of the stand or of the site: i.e., size of trees, density of stands, origin of stands such as planted or natural; dominant textural class of the soil profiles, soil drainage classes, presence or absence of restricting profile layers. Using a transformed expression of "percent of trees damaged" as the dependent variable, we made multiple regression analyses and chi-square statistical tests to determine the relative influence of some of these variables. The following results are based in part on these statistical interpretations of the data.

Results

Significantly greater wind damage occurred on soils with restrictive layers in the profile. Fifty-one percent of the trees on plots where soil profiles contained a restrictive layer in the profile were damaged, as compared with 7 percent on plots where soil profiles showed no restrictive layer.

In comparison with other soils sampled, wind damage was also significantly greater on soils with moderately coarse textured profiles. Approximately 30 percent of the trees on such profiles were damaged, as compared with only 5 percent on the medium and fine textured profiles.

Wind damage to planted stands was significantly less (but only at about the 10-percent level) than it was to naturally occurring stands. None of the other items tested proved to have any statistical significance in relation to wind damage.

There was no damage on 31 of the 102 stands studied, but at one location all trees were damaged. Some damaged trees remained standing, but root systems were displaced from original positions, causing serious permanent damage (Fig. 2).

Many of the damaged trees were completely toppled over. They fell in one of three ways: (1) The soil mass occupied by the root system was lifted as the tree fell, leaving a depression and adjacent root mound on the windward side of the fallen stem. This was the most common type of toppling noted. (2) Lateral roots on both sides and approximately at right angles to the direction of the wind did not

[1]The solum may be defined simply as the genetic soil developed by soil-building forces. In normal soils, the solum includes the A and B horizons, or the upper part of the soil profile above the parent material (*6*).

TABLE 1.—FREQUENCY OF SAMPLED STANDS BY SOIL SERIES, PROFILE TEXTURAL CLASSES, DRAINAGE CLASSES, TYPICAL, AND NONTYPICAL PROFILES

Soil series	Drainage class	Profile characteristic: Typical	Nontypical
	Moderately coarse textured profiles		
		— Number of stands —	
Lakeland	Excessive	1	—
Lakeland (terrace phase)	Excessive	....	1
Norfolk (thick surface phase)	Well to excessive	12	6
Rumford (thick surface phase)	Well to excessive	1	—
Kalmia (thick surface phase)	Well to excessive	1	—
Norfolk	Well	4	4
Klej	Moderately well	1	—
Woodstown	Moderately well	5	—
Dragston	Somewhat poorly	1	....
	Subtotal	26	11
	Medium textured profiles		
Marlboro	Well	3	—
Atlee	Moderately well	12	—
Goldsboro	Moderately well	4	1
Izagora[1]	Moderately well	6	—
Dunbar	Somewhat poorly	2	2
Lynchburg	Somewhat poorly	1	1
Othello	Poorly	4	—
	Subtotal	32	4
	Fine textured profiles		
Craven-like[1]	Well	1	—
Craven	Moderately well	5	—
Lenoir	Somewhat poorly	6	1
Bladen	Poorly	3	—
Leaf	Poorly	1	—
Coxville	Poorly	11	—
Elkton	Poorly	1	—
	Subtotal	28	1
Total number of stands sampled		86	16

[1]Uncorrelated soils.

fail. Trees toppled over in the direction away from the wind, pivoting on the roots that did not fail. The entire root system on the leeward side was forced into the soil as the tree toppled, forming a deep depression beneath the stump of the fallen tree (Fig. 3). Roots on the windward side failed under tension but left little evidence of a depression on that side. (3) The stem settled into the soil below its original level, apparently under swaying wind action. When toppling, it appeared in some cases that the stem had been drawn downward and backward into the soil under tension of roots that did not fail (Fig. 4). In these cases only a slight soil elevation occurred, in place of a root mound commonly associated with windthrown trees, and no depression caused by root displacement was noted. This type of toppling was found only on soils with moderately coarse textured profiles where a

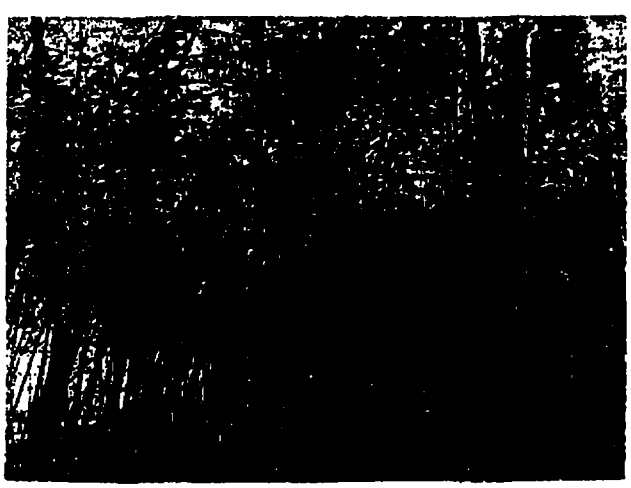

FIG. 2.—Trees tilted but remaining upright in a plantation on Lakeland loamy sand (terrace phase). The root systems have been displaced from their original positions and serious damage to the trees has occurred.

FIG. 3.—A tree on Atlee very fine sandy loam that pivoted on remaining lateral roots when toppled in the direction of the wind. Note the depression beneath the stump (in which the axe handle extends) caused apparently by the root system being forced into the saturated soil.

restrictive layer existed.

General observations and notes were taken on the characteristics of tree root systems of toppled trees growing on soils with a restrictive layer in the lower profile. Figures 5A and 5B are views of an excavated root system of a large windthrown loblolly pine growing on Norfolk sandy loam, thick surface phase. The d.b.h. of this tree was about 20 inches. The root system is made up of a number of large main vertical roots extending to an approximate depth of 48 inches. At this depth, at contact with the restrictive layer in the profile, the main roots had given way to a series of smaller ramifying horizontal roots that had fused together into a broad, flat, woody surface. A few thickened stubby roots penetrated beyond this level into the restrictive layer. Figure 5B shows the root system lying on its side and exposing the broad, flat, woody surface at the 48-inch depth. The observations are generally in agreement with other studies indicating the influence of such soil characteristics as restrictive layers on the growth of tree roots.

The results of this study agree with recorded information on hurricane damage. For Hurricane Hazel in 1954, there was little rainfall east of the storm's eye. Here, tree damage involved mostly broken or bent trees (*8*). Areas west of the eye received torrential rains, and uprooting of trees was common. In the present study of Hurricane Donna, damage was assessed only in areas west of the storm's eye. Tree damage from Donna was mostly uprooting or severe root injury. Little damage was recorded for stem damage to trees that remained standing. Curtis (*2*) discussed the New England Hurricane of 1938 and stressed the tree damage resulting from heavy rains that preceded the storm.

Nelson and Stanley (*5*) related the degree of tree damage to thinning in East Texas following Hurricane Audrey in 1957. They found much more severe damage in heavily thinned slash pine plantations where residual stocking was low than in lightly thinned plantations where residual stocking was higher. Statistical tests of our data were inconclusive with respect to tree damage related to residual stock-

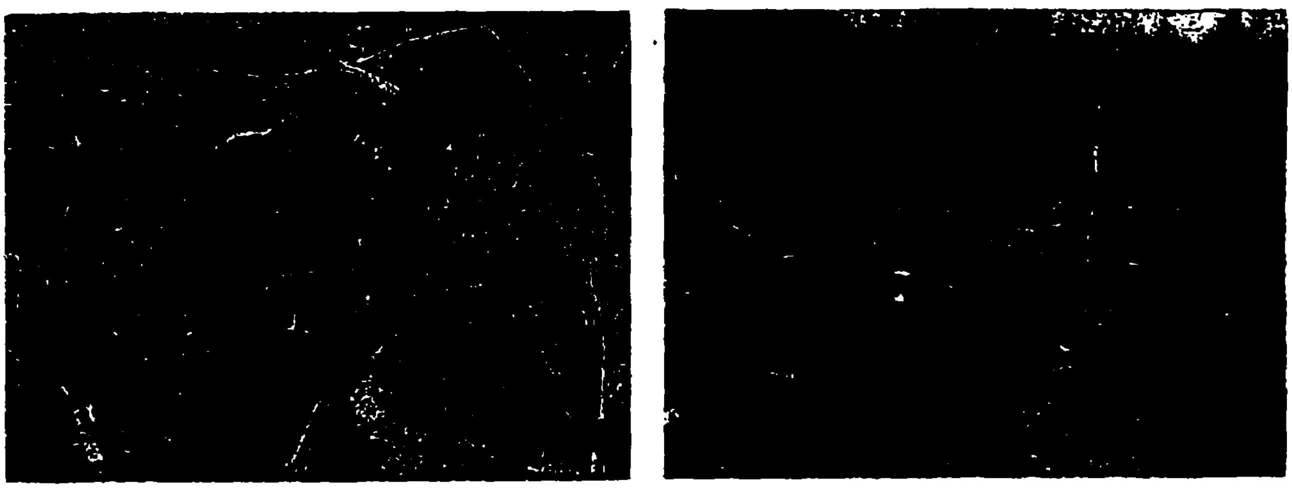

FIG. 4.—Some trees seemed to have settled into the soil under the swaying action of the wind before toppling. This type of windfall was noted only on soils with moderately coarse textured profiles with deep-lying restrictive layers. This soil was a nontypical Norfolk loamy sand. (*L*) The butt log of this tree was salvaged by winching it from the soil depression before cutting. The depression at the 3-foot stump height is about 1 foot deep. (*R*) The first 12-foot log of this tree was left embedded in the soil where it fell. Axe is over the stump.

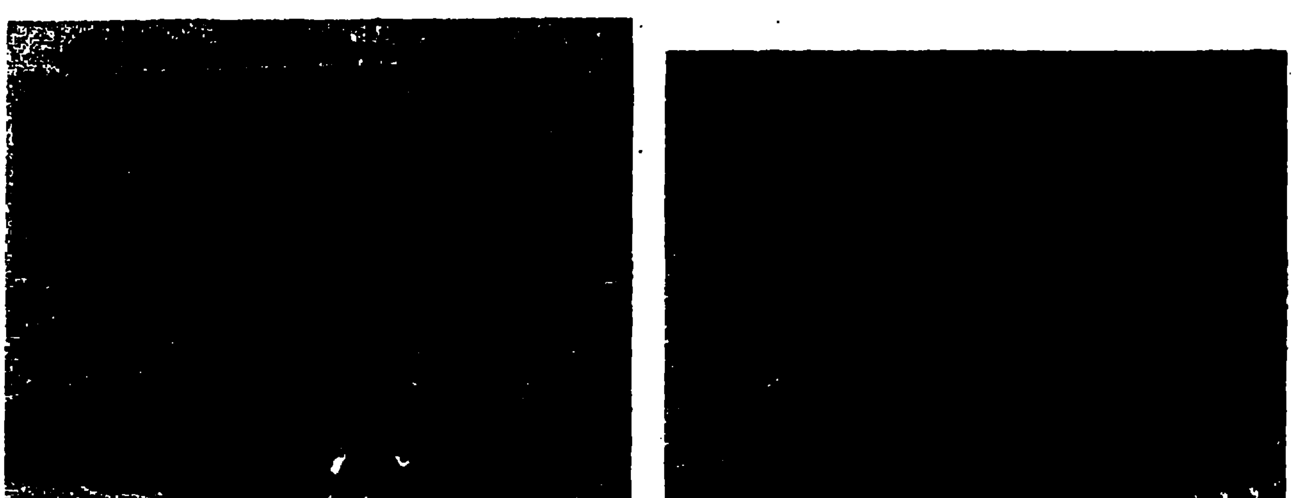

FIG. 5.—(*L*) Excavated and inverted stump of a loblolly pine. (*R*) View of same stump lying on its side. Note the absence of normal root development. At a soil depth of 48 inches a restrictive layer of impervious material was found. The root system was flattened and grew into a broad continuous woody surface just above the restrictive layer. The soil was a nontypical Norfolk sandy loam, thick surface phase.

ing of thinned stands.

Croker (*1*) observed longleaf pine in Alabama following Hurricane Flossy. In a zone receiving 9 inches of rainfall during the storm, he found 90 percent of the blown-down trees were on soils underlain by clay or sandy clay at a depth of 24 inches or less. He assumed that restricted root development, along with soil saturation above the less permeable clay layer, was responsible for the severe blowdown. Our results appear to corroborate his findings.

Tree damage in this study appeared to result from a combination of high wind, excessive soil moisture and failure of the soil to provide adequate support. The strength of a soil in giving adequate tree anchorage and support comes from adhesive, cohesive, and friction properties of the soil. These properties are determined by size, shape, and arrangement of the soil particles and by the nature of the water films surrounding them. Silt and clay soils lose their cohesion and become plastic in the presence of increasing amounts of water. At a very high moisture content, the soil loses its plastic properties and approaches a fluid in its mechanical properties (*9*). The soil then has little or no shearing strength and is readily deformed. The relatively low degree of damage found on the silt and clay soils of this study (especially in the absence of fragipan-like restrictive layers that prevented adequate root and water penetration) suggests that these soils were able to retain a high degree of cohesion.

Sandy soils derive their strength for tree anchorage principally from shear resistance due to internal friction. This internal friction is proportional to the compressive forces between adjacent soil particles. The compressive forces are due to the weight of the soil. Under intense vibration of a water-saturated loose sand, part of this compressive force is transferred to the water, which has essentially no shear strength, and the result is a marked weakening of the soil to resist shearing (*5*).

Because of the higher permeability rates, the sandy or moderately coarse textured profiles of this study became saturated more rapidly than finer textured profiles. When restricting layers were present, they created "perched" water tables. Excess water within the root zone, especially on soils with the restrictive layers, reduced the shear strength of these moderately coarse textured soil profiles. We believe this reduction in shear strength, together with inadequate depths of rooting in soils with a restrictive layer, accounts for some of the severe blowdown during Hurricane Donna.

With variation in wind speed, a tree bends and sways, and the tip is reported by Mergen (*4*) to oscillate in an elliptical pattern. This action places stress alternately on different sides of both the stem and the root system. Where soils lose their shear strength because of moisture, the tree root system may act as a giant stirring agent as a tree sways in the wind before it falls. This may explain the type of windfall illustrated in Figure 4 that was noted on moderately coarse textured profiles with restrictive layers. Here the weight of the tree seems to have forced the root systems deeper into the soil before toppling occurred.

There are some immediate practical uses for these findings. For instance, where timber stands are to be chosen or established for special research, high-value or long-time purposes, soil areas that predispose them to hurricane damage can be avoided. Such attention would apply to choosing seed production areas, establishing seed orchards, or outplanting rare and highly valuable trees. Planners of such activities should be particularly alerted to the hurricane hazards in this area on soils with moderately coarse textured profiles and on soils where a restrictive layer prevents adequate root and water penetration. Soil maps are helpful in this respect and the on-site assistance of a soil scientist may be an added insurance worthy of consideration.

Summary

Damage to recently thinned loblolly pine stands by Hurricane Donna was studied in an eight-county area of the coastal plain of Virginia and North Carolina. The area extended about 60 miles northwesterly from the path of the storm's eye. This area received torrential rains preceding and during the storm.

Damage was assessed by determining the percentage of trees injured by the storm. Stand and soil characteristics were determined and recorded for sampled areas. Tree damage was recorded separately for "main stem" (breakage) and for "root system" (displacement from original position or blowdown). Over 99 percent of damaged trees were of the second type. Stem breakage was insignificant.

Damage was more severe on soils having moderately coarse textured profiles than on soils with finer textured profiles. It was most severe on nontypical soils of the series studied in which a restrictive layer occurred within the profile that tended to retard the taproot and water penetration. It is suggested that root systems fail to give adequate support to healthy loblolly pine trees during hurricanes because of reduced soil shearing strength when soils are excessively wet. It is also suggested that seed production areas, seed orchards, and other particularly valuable plots should not be established on such areas.

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ORIGIN AND DEVELOPMENT OF WHITE SPRUCE ROOT-FORMS

by

J. W. Bruce Wagg

Sommaire en français

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ABSTRACT

Typical root-forms for immature white spruce, *Picea glauca*, in Alberta and the Northwest Territories are an elongated taproot developed on well-drained soils of nearly uniform texture, a restricted taproot on soils with either textural changes between horizons or with compact horizons and monolayered with or without a vestigial taproot on soils with excess moisture near the surface. A fourth multilayered form develops with increasing moss layer and periodic alluvial and lacustrine deposits. Eight variations of the typical root-forms are interpreted according to soils, sites and the spatial organization of roots during morphogenesis. The orientation of roots and the interaction of growth among roots in a system influence form mechanically and physiologically. Secondary roots occur in all root-forms and are a significant part of the restricted taproot and monolayered forms. The multilayered root-form is totally dependent upon the development of secondary roots. The time required to establish individual roots and the interaction between the growth of individual roots within a system are related to the growth of the trunk. Height growth of a tree is small during the period of root establishment and of root replacement.

CONTENTS

ORIGIN AND DEVELOPMENT OF WHITE SPRUCE ROOT-FORMS

by

J. W. Bruce Wagg[1]

INTRODUCTION

The premise that a single root-form is inherent to white spruce[2] is erroneous, as is the concept of a plate-like (monolayered) form of large lateral roots with sinkers to variable depths. While some spruce are monolayered, others vary from a single whorl of laterals with a large elongated taproot to many whorls of superimposed laterals (multilayered) without a taproot. A myriad of intervening forms exist.

To ascribe a single root-form to white spruce is impossible owing to the interaction of different soil properties with changes in site during the life of the tree. Further difficulties arise in explaining root development when soils and sites are considered separately from the spatial organization of roots during morphogenesis.

Variations of root-form which occur among soils with different textural and structural properties and in the presence of excess moisture and anaerobic conditions have been reported often. More recently the role of secondary (often called adventitious) roots has been recognized in the development of the multilayered form after alluvial and lacustrine deposits (Jeffrey 1959; Wagg 1964), growth of mosses (LeBarron 1945; Koŝĉeev 1953), changes in water tables and soil frost (Krasiljnikov 1956).

Morphogenic variations of root-form result from differences in orientation of individual roots in decayed wood, moss, humus and soil, in numbers and organization of roots at the rootstock and in the growth rates of individual roots.

This paper presents observations on the following aspects of root-form of white spruce:

(1) the occurrence of secondary roots and their role in the development of root-forms;

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[2]Scientific names are listed in Appendix 1.

(2) the influence of (a) soil properties, (b) site modifications during the life of the tree and (c) spatial organization of roots during morphogenesis on the development of form; and

(3) relationships between the development of the root system and the growth of the trunk of the tree.

The illustrated root systems are case histories which show a wide range of root-forms and some variations.

TERMINOLOGY OF ROOTS

Root-form refers to the arrangement of all roots at the rootstock and vertical roots from other roots near the rootstock. The nomenclature of roots attached to the rootstock is expanded from Lemke (1956). Figure 1 shows a composite of white spruce root-forms. Five types of lateral roots are distinguished.

Lateral is applied to lateral roots of the monolayered root-form with a single whorl of laterals, or to lateral roots in general when more precise terminology is not required.

Infralateral is a lateral root in the lowest whorl of lateral roots from the rootstock.

Supralateral is a lateral root in the highest whorl of lateral roots from the rootstock.

Interlateral applies to all roots between the infralateral and supralateral roots. In multilayered root-forms the interlaterals may comprise several whorls of roots and may be further distinguished by numbering the whorls upward.

Bur is a young (1- or 2-year-old) usually secondary root growing from a burl on the rootstock. Bur roots occur in groups and a burl forms from continual die-back and regrowth of roots.

The terminology of oblique and vertical roots is evident in Figure 1. Heart roots originate from lateral roots near the rootstock while proximal roots originate within the rootstock.

The term secondary is used in this paper to describe roots growing from the stems and branches of trees. Primary is used for roots originating below the hypocotyl and adventitious describes roots which develop out of sequence from either primary or secondary roots. Adventitious has been used by various authors to describe roots growing from stem and branches as well as from other roots. Sirén (1950); Veretennikov (1959) *et al.* have retained adventitious in the sense of Büsgen and Münch (1929) by applying the term to roots originating out of sequence from other roots.

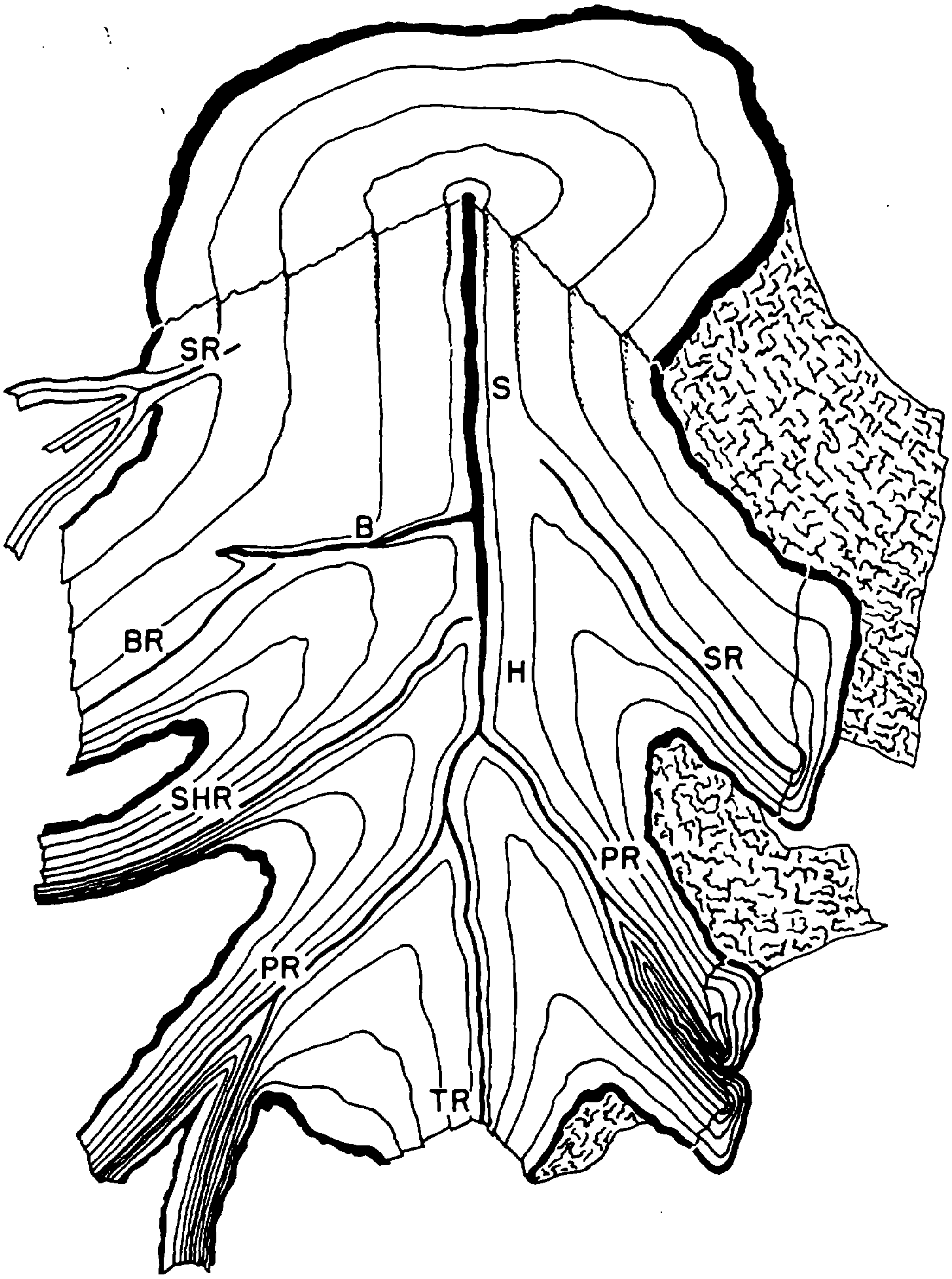

Figure 2. Dissection of rootstock showing roots in relation to hypocotyl (H), *stem* (S) *and branch* (B): *primary root* (PR), *supra-hypocotyl-root* (SHR), *stem-root* (SR) *branch-root* (BR) *and taproot* (TR).

Within the base of the hypocotyl the resin canals disappear (Figure 3D) and a complicated rearrangement of tissues occurs throughout until (q.v. Dangeard 1892; Hill and de Fraine 1909) a pith-like structure appears (Figure 3B) near the top.

Immediately above the hypocotyl the pith is small and filled with cells (Figure 3A) in contrast to the large pentagonal or polygonal structure found in the upper parts.

When the hypocotyl is overgrown, its upper and lower limits are difficult to ascertain because of the gradation into triarch or diarch xylem at the base and into pith at the top.

Primary roots originate below the hypocotyl and are connected in sequence by two central resin canals to the resin canals of other roots and finally to the taproot. Sequential growth means that the lineal growth of any year is connected directly to the growth of the previous year.

Adventitious roots originate out of sequence from either primary or secondary roots and are two or more years younger than the root to which they are attached. The resin canals originating within the root are connected to those of the root from which they developed.

Secondary roots from dormant buds on stems and branches are connected to the pith by parenchymous tissue (Bannan 1942). Dissections of rootstocks show the resin canals terminating in the annual rings of the wood. Secondary roots are termed stem-roots or branch-roots depending upon the *point of origin. A stem-root at the top of the hypocotyl is a supra-hypocotyl-root.*

Secondary roots develop on white spruce in many different soils and sites. They develop from the stem and branches of trees when these are covered by humus, moss or soil (Bannan 1940; Jeffrey 1959; Wagg 1964). Secondary roots also occur on other species of spruce (LeBarron 1945; Meyer 1938; Nägeli 1930; Koščeev 1952, 1953; Hustich 1954; Denisov 1960 *et al.*) and root-form differs from white spruce only in degree.

Secondary roots develop throughout much of the life of a tree and have been observed on 2-year-old seedlings and on 135-year-old trees (Figure 4). The most frequent occurrence is probably between 3 and 20 years.

MATERIALS AND METHODS

The 12 root systems were selected from 60 immature trees taken from a variety of sites in Central Alberta and the Northwest Territories. These were supplemented by observation of several hundred root systems exposed on recent burns.

The central core of the rootstock was sometimes sectioned to determine the presence of pith or root structure, as the pith of both stems and branches may show a nodal structure with distinct demarcation of growth between years, a feature not found in hypocotyl or root.

Annual growth rings are usually present in roots, and partial or indistinct rings often occur. However there is great variation in the size of rings which at times makes the determination of the age of some roots difficult, if not impossible. Occasionally growth rings are found near the rootstock, are absent for a distance and present again further along the root.

TYPICAL ROOT-FORMS

Variations in root-form of conifers arising from textural and structural differences among soils and modifications of site by excessive moisture and growth of moss are well documented: Aaltonen 1920; Laitakari 1927; Vater 1927; Pöntynen 1929; Priehäusser 1939; Bannan 1940; Koščeev 1953; Krasiljnikov 1956; Horton 1958; Köstler 1962; Wagg 1964.

Secondary roots account for the many different root-forms of spruce and for changes in form which occur during the life of a tree. The root system of a juvenile tree with four large laterals and a taproot may grow in one of several different ways. Three examples are presented.

1. No change in form occurs when all roots grow at similar rates and secondary roots do not develop. The four laterals form an incomplete whorl around the rootstock and the elongated taproot-form results.

2. Growth of the taproot may be restricted by the development of secondary roots. When two lateral roots are separated by a wide gap on the rootstock and the trunk is connected directly with the taproot, secondary roots may develop in this area. The addition of one or more secondary roots to the four primary roots of the juvenile completes a whorl of lateral roots around the rootstock. This reduces, and may eventually stop, the growth of the taproot. The restricted taproot-form of the immature tree is composed of large laterals and a small taproot.

3. When a build-up of moss or alluvium occurs around the trunk of the juvenile tree, secondary roots develop in this layer above the primary roots. Should the secondary roots grow to a large size, the primary lateral roots and taproot will slow down in growth and may eventually die. With continual re-rooting, the immature tree develops a multilayered root-form of several superimposed layers of lateral roots.

Elongated Taproot-form

The elongated taproot-form of Tree I (Appendix 2 and Figure 5) developed in well-drained aeolian sands. The root system has four large lateral roots (<u>A</u>, <u>B</u>, <u>C</u> and <u>D</u>) and a large taproot (<u>M</u>) which is connected to the trunk between <u>A</u> and <u>D</u>. Young laterals (e.g., <u>F</u>, <u>G</u>, <u>H</u>) occupy the gap on the rootstock between <u>A</u> and <u>D</u>. All roots are of primary origin.

The tree was established on mineral soil and developed a long taproot (M), tap-lateral (K) and two laterals (B and C) by the 15th year (Figure 8A). With development of A and D, all large roots except N were present at the 20th year. The young laterals developed from bur roots after the 33rd year. The taproot with numerous tap-laterals grew steadily in length from an early age. It was neither restricted by the aeolian sands or affected radially by an overgrowth of laterals. The taproot was connected, on part of its periphery, to the trunk through a gap between laterals A and D. The young laterals in the gap did not restrict the growth of the taproot as the underlying tap-lateral K was expanding in growth. The thin and dry L-H layer was not suitable for the development of secondary roots.

Spruce with elongated taproots and without secondary roots are uncommon. Usually the taproot is restricted and branched at variable depths. While secondary roots may develop they do not commonly grow to a large size on well-drained soils.

Restricted Taproot-form

As the tree matures the elongated taproot often becomes a restricted taproot. Growth restriction may be owing to either soil texture, structure, moisture and frost (see Dahurian larch and frost, Umkin 1958), or because of rapidly growing lateral roots. Examples below show the influence of soil texture and soil structure on taproot and proximal root growth.

Restricted by Soil Texture

The restricted taproot-form of Tree II (Appendix 2 and Figure 6) resulted from a textural change between soil horizons. The root system has four large laterals (A, B, C and G) and an aborted and distally contorted taproot (N); B and C are secondary roots. A number of bur roots are in the gaps between the large laterals.

Morphogenesis of the system is shown in Figure 8B. The tree, established on mineral soil, developed a large taproot (N). At 15 years the tree had five primary laterals (A, D, G, H and O), two secondary laterals (B and C) and a proximal (E). The primaries A and G grew to become the large roots along with the secondaries B and C in the immature system.

The upper soil layers were favorable for growth of the taproot, particularly tap-laterals. Further vertical development of the taproot was restricted by the mechanical action of the gravel layer. Although secondary roots formed in the feather moss and humus, they did not grow large enough, between laterals C and G, to restrict growth of the taproot.

Restricted by Soil Structure

The restricted proximal roots of Tree III (Appendix 2 and Figure 7) developed in Solonetzic soil. The system of supralateral, infralateral and proximal roots resembles a bilayered and restricted taproot-form. The supralaterals were increasing in growth, and organized into five groups: A, B-C, E, D and P-Q. The infralaterals, K, L, O and F were growing steadily;

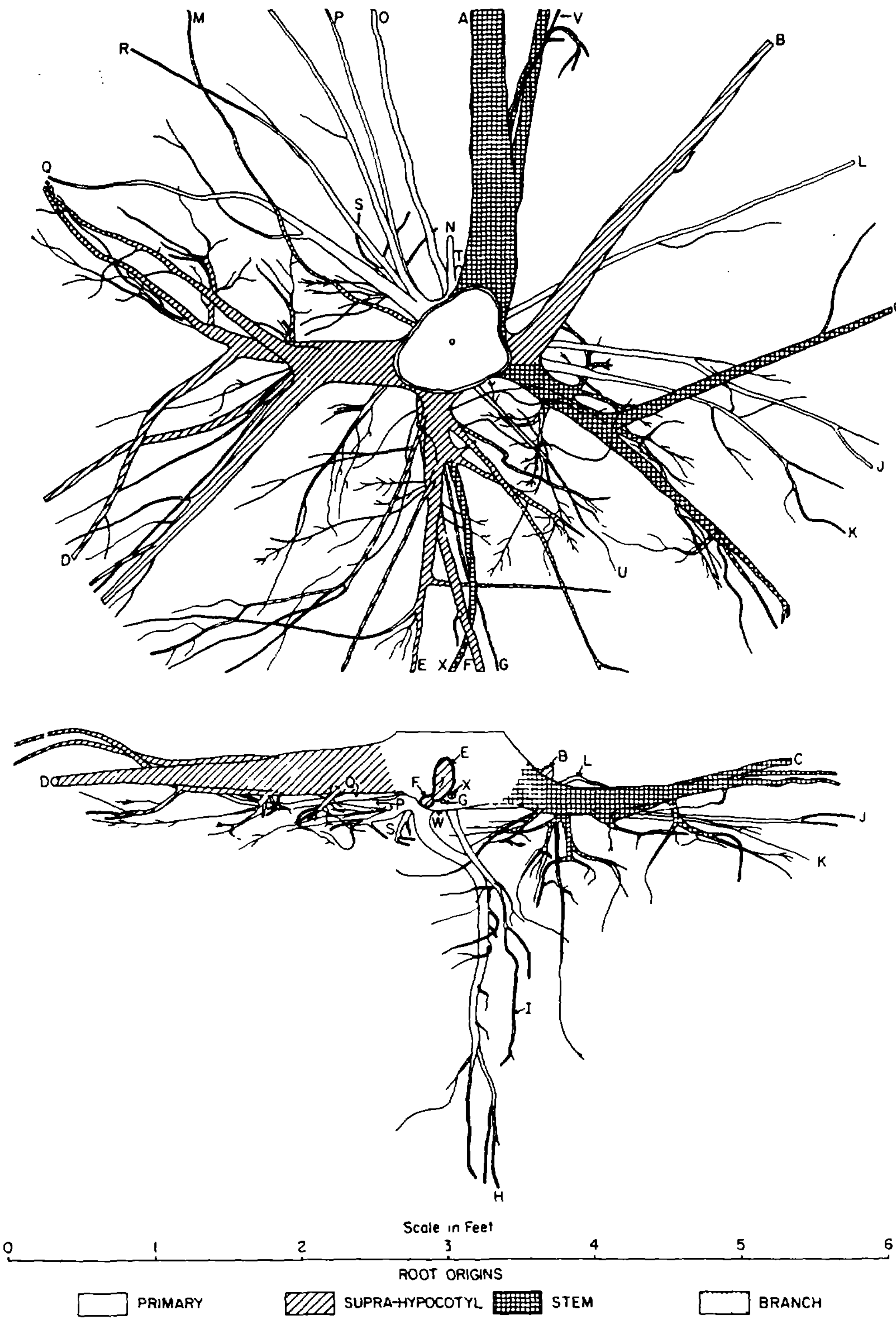

Figure 7. Tree III: Restricted proximal roots from compacted Solonetzic soil with large secondary lateral roots.

G, J, R and V were decadent; and T, H and N were dead. The proximal roots were contorted proximally and capillaceous distally. The taproot (W) persists as a partially overgrown stub at the base of the rootstock. All large supralaterals are of secondary origin.

Stages in morphogenesis are shown in Figure 8C. The tree developed a taproot (W) and primary (N) and secondary (B, E and N) lateral roots by 10 years. The proximal roots (H, I and S) developed from the taproot between the 11th and 12th years and the taproot died and rotted away. Five secondaries (A, B, C, E and D), which grew into large supralaterals, developed by the 15th year. By the 20th year the primary infralaterals O, Q and R developed in the gap between A and D to close the connection between the proximal roots H and I and the trunk. Later when the proximal roots became decadent they were connected to the trunk through contorted tissue at the rootstock.

Proximal roots, contorted by the blocky B horizon, developed capillaceously distally in the compacted and columnar structured C horizon. A build-up of humus about the seedling stem accounts for the development of secondary roots. The hypocotyl was S-shaped (Figure 8C) bringing the stem in contact with the humus at an early age.

Other Factors

Taproots are often restricted at some period during morphogenesis through either horizontal growth in the seedbed or overgrowth by lateral roots. Seedlings will develop contorted taproots on decayed wood, raw humus and poorly-drained seedbeds. The horizontal growth results from the higher moisture content of decayed logs, the improved nutrient and moisture content of the mineral soil-humus interface, impediments in humus and decayed wood, and anaerobic conditions of poorly-drained soil.

Seedlings with elongated taproots may exhibit a restricted taproot in the immature tree. In such cases, the laterals develop rapidly, encircle the rootstock and retard the growth of the taproot. The laterals and trunk continue to enlarge at a faster rate than the taproot until a restricted taproot-form develops.

Monolayered Root-form

Immature root systems occur without vestigial taproots. These originate from seedling systems in which the taproot is either aborted, contorted and aborted, or degenerate at the rootstock. The lateral roots have either overgrown or outlived the taproot. They are described according to the form in the seedling and dwarf which is an old tree of seedling size.

Developed from Aborted Taproot of Juvenile Tree

The monolayered or partially bilayered root-form of Tree IV (Appendix 2 and Figure 9) resulted from overgrowth of the aborted taproot in the juvenile tree growing in shallow soil. The supralaterals A, C, D, E, F, G and H, which are of primary and secondary origin, form a complete whorl around the root-stock. The infralaterals B and I form a partial second whorl. *No taproot is present.*

The monolayered form developed from the restricted taproot-form of the juvenile tree. By the 10th year (Figure 12A) the aborted taproot (L) and the primary laterals D, H and F developed, and by the 15th year the remainder of the primary laterals B, E and I. The primaries constituted the large roots of the immature system. With rapid tree growth between the 15th and 20th years, the primaries overgrew the taproot which aborted due to excessive moisture in the Cg horizon. Later, with an increase in the depth of the feather moss and humus layer, the secondary roots A, C, G, J and K developed.

Tree IV is a compressed variant of the monolayered form and is characteristic of trees growing on shallow soils and depressions in bedrock where vertical penetration of roots is prevented. The proximal portion of lateral roots are rounded or horizontally oblong rather than a vertical I-shape in cross section. Superimposed laterals are compressed and sometimes coalesced; vertical roots are contorted and undulated to follow the contours of the bedrock. The origin of the roots will vary but systems composed of primary and secondary roots are found most commonly.

Developed from Contorted and Aborted Taproot of Seedling

The monolayered root-form of Tree V (Appendix 2 and Figure 10) developed from a contorted and aborted taproot of the seedling growing in humus.

The root system has supralateral, infralateral and proximal roots of primary and secondary origin. Of the five supralaterals which form a complete whorl around the rootstock, A and H are primary roots and C, D and E are secondary roots. The small supralaterals G and J are secondaries. The infralaterals B, I and K and the proximals L and F are primaries. A sinker from H appears on the diagrams as a proximal. The rootstock of another tree caused the bilateral orientation of roots A and D.

Morphogenesis of the root system is shown in Figure 12B. By the 10th year the tree had a contorted and aborted taproot (M) which developed in burned humus of the L-H layer and a single primary lateral root (K). Other primaries (A, B, H and I) and one secondary (C) developed before the tree was 15 years old. The taproot was overgrown by roots A and B. The secondary laterals B and J, of which B grew to a large size, developed in the 17th year and E in the 29th year. The proximal roots L and F developed in the 22nd and 24th years and, with the exception of E and G, were the youngest roots in the system. Proximal and sinker roots were short, terminating in the Ae horizon as a result of fluctuating moisture.

While the monolayered or partially bilayered root-form, without a vestigial taproot, appears uncommonly, the restricted taproot and especially the contorted taproot variant occurs often on Podzols and Gleysols. Wet soil underlying humus precludes vertical growth of roots; sinkers are aborted and branched and taproots contorted and aborted in the humus or upper mineral soils (cf. Norway spruce, Kreutzer 1961). Secondary roots develop at an early age in the moist humus. Typical monolayered forms show rapid growth of primary and secondary roots which either choke the growth or completely overgrow the taproot at an early age.

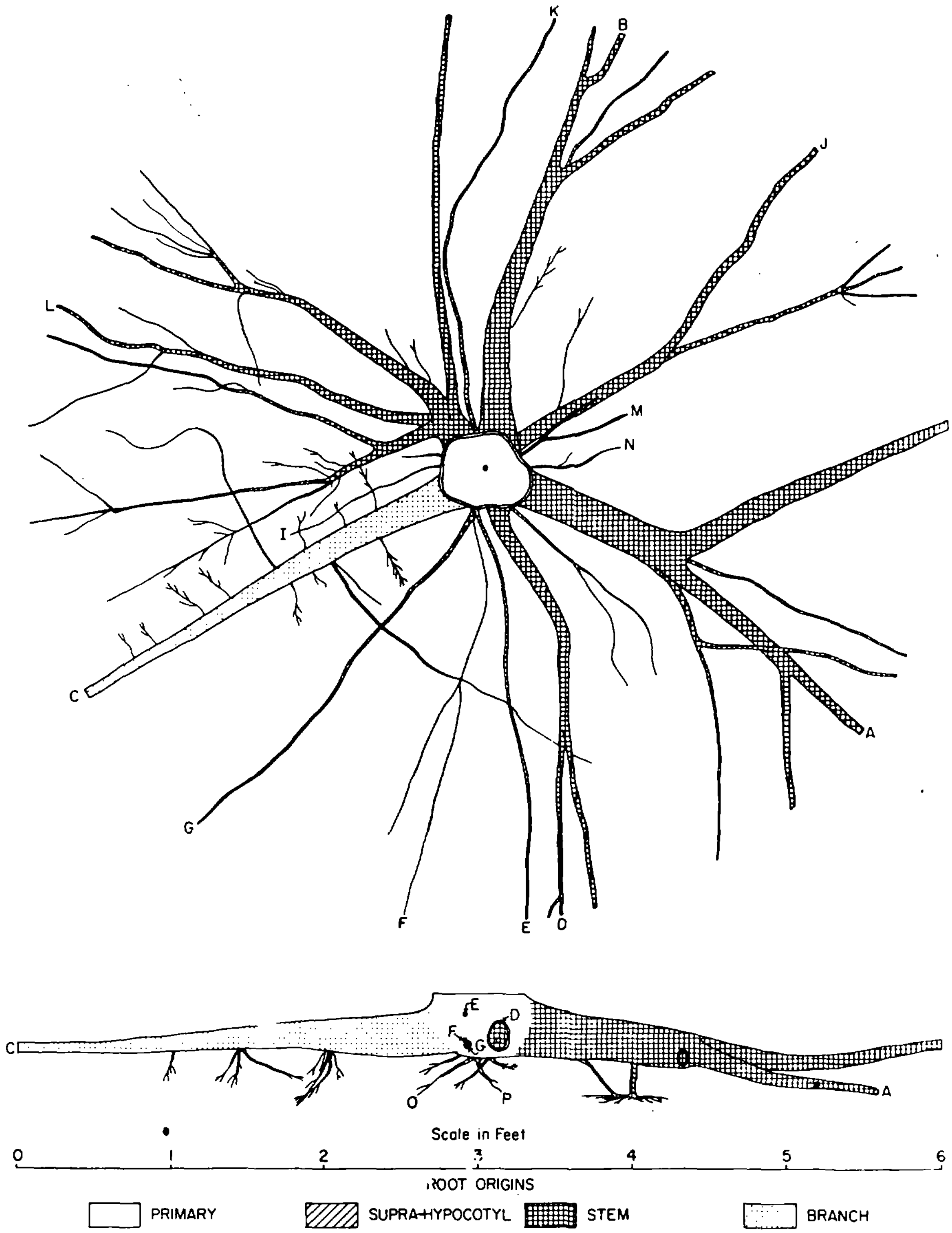

Figure 11. Tree VI: Monolayered root-form with large secondary lateral roots resulted from degeneration of primary roots of dwarf tree in waterlogged soil.

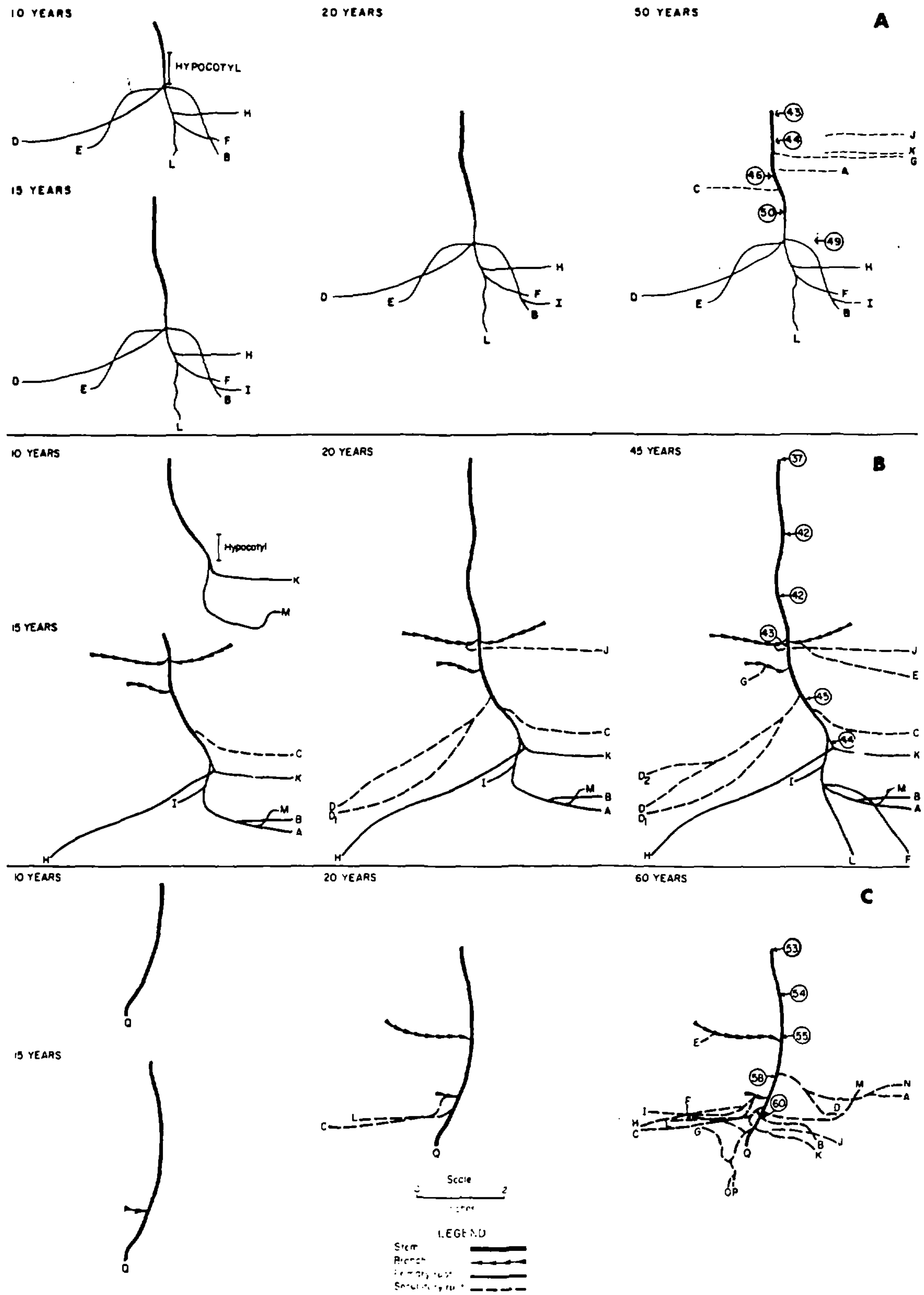

Figure 12: Anatomical origin and chronological development of roots for Tree IV(A), Tree V(B) and Tree VI(C).

Developed with a Rising Water Table

The multilayered root-form of Tree VIII (Appendix 2 and Figure 14) developed with a gradual rise in the water table and an increase in the depth of the humus and feather moss layer. The vertically compact system has seven whorls of lateral roots. All roots, except W and X, are of secondary origin. The size of roots in each whorl is graded upwards with the infralaterals being the smallest and the supralaterals the largest. The infralaterals and a number of interlaterals are dead. As none of the whorls completely encircle the rootstock, there is a gap between the laterals of one whorl and the whorl below. The live interlaterals show decadence and the supralaterals a steady rate of growth.

Morphogenesis is shown in Figure 15B. The tree became established on mineral soil or thin humus and developed a small primary root system (W and X). As the moss and humus layer grew thicker, the tree re-rooted from the stem and branches. The cyclical processes (of re-rooting, growth of moss and re-rooting) continued and secondary roots were still developing from the trunk near the surface of the moss.

Continued growth of feather moss progressively delayed the dissipation of soil frost in the spring and the water table rose nearer the surface. Dead roots persisted on the lower half of the rootstock: the lowest ones, being continually in waterlogged soil, were resin impregnated; and the upper dead roots, in the region of a fluctuating water level, contained in a fibrous decay.

Black spruce and tamarack developed a similar multilayered form on sites with a rising water table and on sphagnum. The form was uncommon to white spruce on sphagnum sites with high water tables and thick layers of moss since most trees, which were rooted on hummocks or decayed logs, had either a poorly-developed multilayered or monolayered form.

Developed after Lacustrine and Alluvial Deposits

The well-developed multilayered root-form of Tree IX (Appendix 2 and Figure 16) resulted from two different lacustrine deposits. The system has six superimposed whorls of lateral roots of which interlaterals A, F, H and B near the top of the rootstock are the largest. All roots are of secondary except the contorted taproot I and the infralateral D.

The tree became established on a 2-inch humus layer. By the 5th year a contorted taproot (I) developed in the underlying sands and an infralateral (D) in the humus. Lacustrine sands were deposited to a depth of 31 inches in the 15th year and several large secondaries developed by the 20th year in the upper part of this deposit. A further 3-inch deposit occurred in the 30th year in which the whorl, composed of R, Q and several bur roots, developed.

The morphogenesis is not typical of multilayered systems in alluvial deposits. Instead of one thick deposit several thin alluvial deposits usually occur during the life of the tree. Secondary roots may develop in each successive deposit. The roots in each superimposed whorl

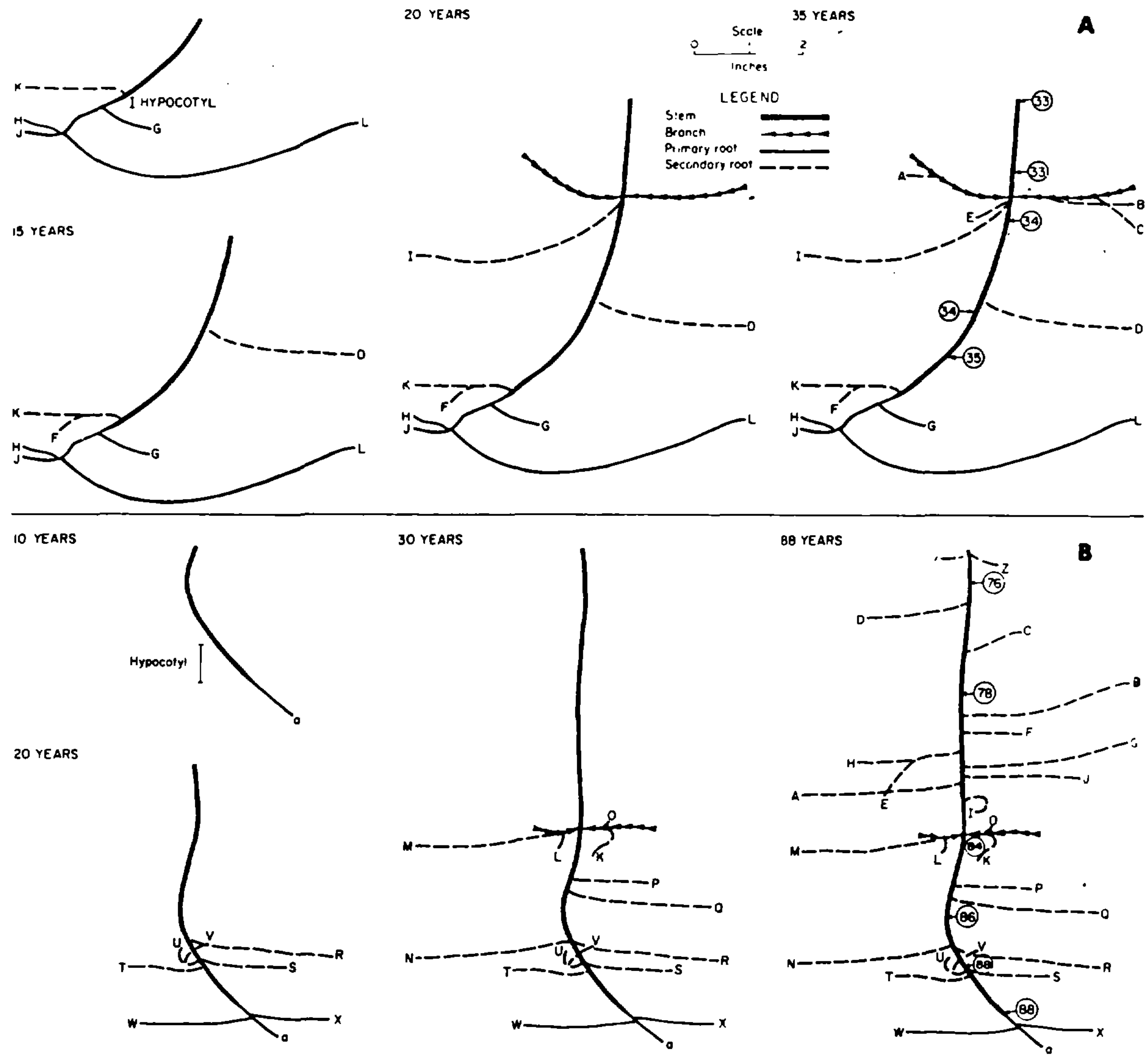

Figure 15. Anatomical origin and chronological development of roots for Tree VII (A) and Tree VIII (B).

are younger and grow to a larger size than those in the whorl below (vid. Tree VIII). The secondary roots of Tree IX developed about the time the 31-inch layer was deposited.

Well-developed multilayered root-forms are common to white spruce and balsam poplar growing on sites subject to periodic alluvial deposits (q.v. Jeffrey 1959; Wagg 1964). They were observed on the alluvial flats of the Peace, Slave and Liard Rivers in the Northwest and Yukon Territories and have been seen throughout Alberta.

MORPHOGENIC VARIATIONS OF ROOT-FORM

Variations in typical root-forms may occur which are not directly attributable to either soils or sites but to the spatial organization of roots during morphogenesis. Spatial refers to the orientation of roots in the rooting medium (a mechanical influence) and to the interaction of growth among roots (a physiological influence) on form.

Orientation of Roots

The greatest variability in juvenile root systems is found on decayed wood. The variations develop in several ways depending upon the place of seedling establishment and moisture.

On dry areas the seedling roots may be confined to decayed wood until the wood deteriorates and the primary roots enter the surrounding soil. As the wood deteriorates, moss becomes established and humus forms over the wood. Secondary roots grow to a large size in the better moisture and nutrient conditions of this moss-humus layer. A bilayered root-form results.

On wet areas, decayed wood situated above the general soil level is suitable for seedling establishment. The primary roots develop rapidly in the decayed wood and small secondary roots develop in the humus and moss on the wood. The result is an elevated variation of the monolayered form with large primary laterals, grouped asymmetrically around the rootstock. The typical form on such sites would be monolayered or partially bilayered with large secondary roots.

On waterlogged areas, seedlings appear on hummocks and decayed stumps above the level of free water. Primary and secondary roots grow downward around the stump or mound in a stilt root-form.

Three morphogenic variations of root-form are illustrated.

Retarded (Growth of Primary Roots)

The retarded variation of the multilayered root-form of Tree X (Appendix 2 and Figure 17) developed on a decayed log on a dry Bisequa soil. The root system is poorly multilayered since the interlaterals and supralaterals form only a partial whorl around the rootstock. All roots except I are secondary. Only the supralateral D and the interlaterals A and C are large and many small roots terminated capillaceously near the rootstock.

Stages in morphogenesis are shown in Figure 19A. The tree, which was established on a decayed log, developed a primary root system within the log but only the primary root I remained in the immature system. A divaricate stem quickly developed and almost all of the secondary roots developed from one branch. By the 15th year the infralaterals, R and S, grew downward through the log to abort in the top of the Bf horizon. Of the other infralaterals (A, F and X), which grew in the humus on top of the log, only A reached a large size. The supralaterals D and E and the

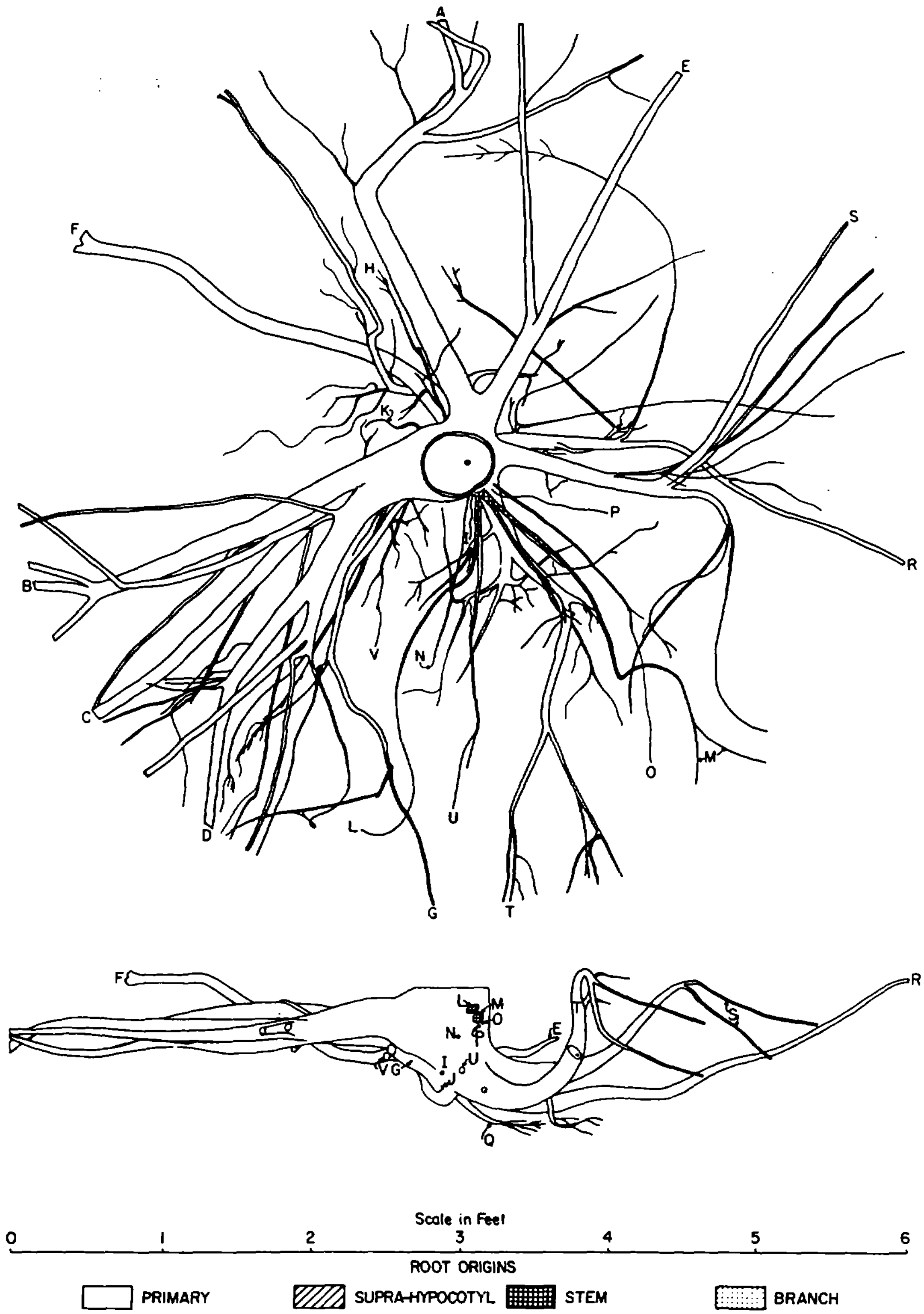

Figure 18. Tree XI: Elevated variation of monolayered root-form with partially bilayered primary roots which developed on the top of a decayed stump in sphagnum.

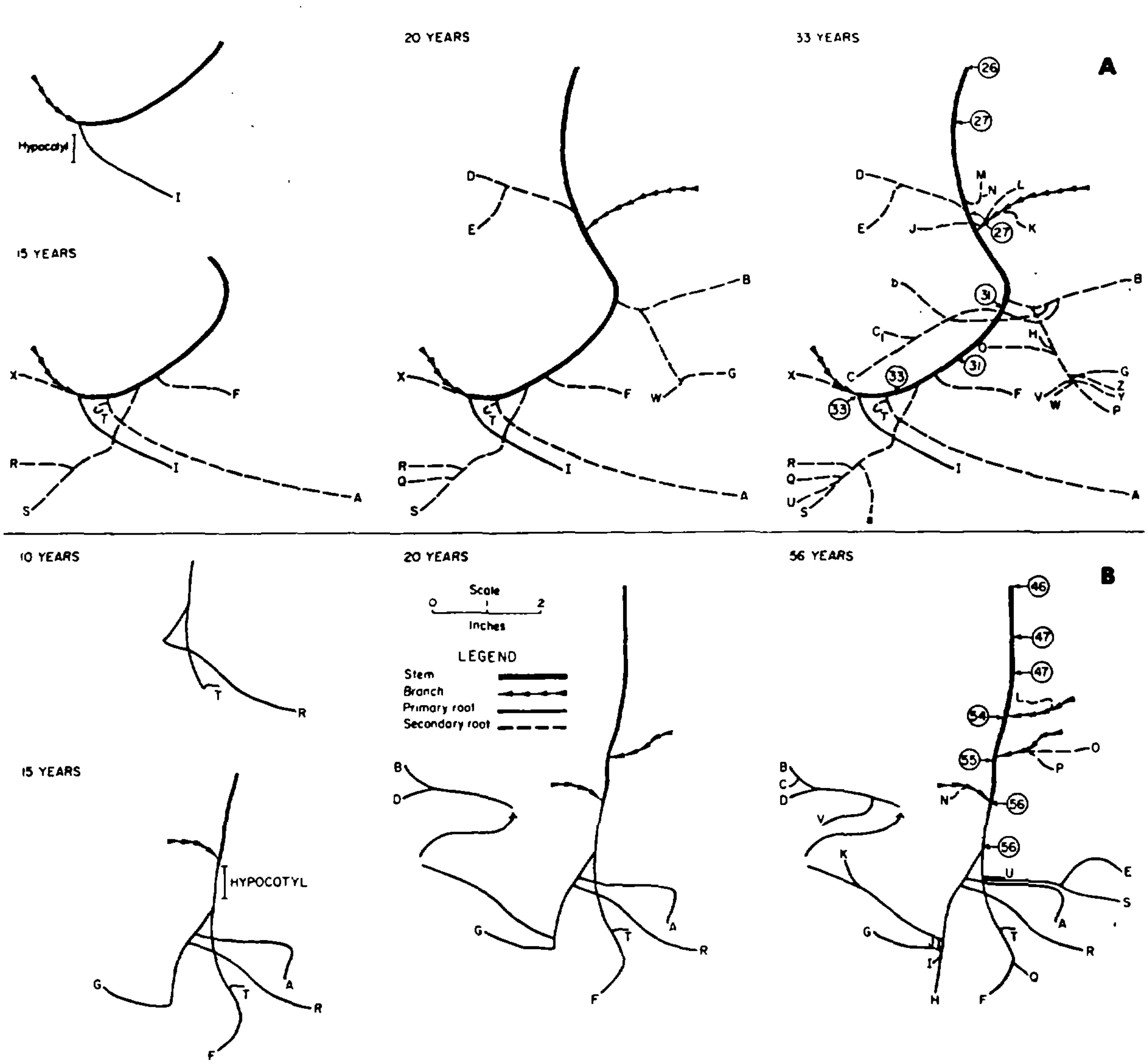

Figure 19. Anatomical origin and chronological development of roots for Tree X (A) and Tree XI (B).

developed above the supralaterals (A, B, H and I); (b) the supralaterals grew obliquely from the rootstock in a stepped-down manner as the sphagnum died, and; (c) the supralaterals terminated near the surface of the dead sphagnum and at the same level as the infralateral roots which would be buried more deeply in live sphagnum.

The complex root-form can be anticipated after alteration of sites by drainage, destruction of the moss cover, or fire. Complex forms require at least two distinct stages in site development, such as the normal development of moss and humus in a stand followed by a destruction of the moss cover.

Interactive Growth of Roots

Interactive growth among roots within a system refers to differences in the growth rate of roots of various ages and sizes. This concept may be clarified by a review of some of the previous root-forms.

Restricted Taproot

While the restricted taproot-form develops on certain soils, it also occurs when a complete whorl of laterals develops above the taproot. This is interactive growth between laterals and taproot.

Neither Tree I nor Tree II shows suppression of taproot growth by the laterals. In Tree I (Figure 5) the taproot is connected directly to the trunk through a gap between laterals A and D. Similarly, the taproot of Tree II (Figure 6) is connected to the trunk between laterals G and H. In neither case did lateral roots completely surround the rootstock, and therefore growth of the taproots was not restricted.

When lateral roots completely encircle the rootstock, the taproot is connected to the trunk through contorted tissue and both radial and lineal growth is suppressed. Suppression of the taproot may occur at any age; the earlier it begins the smaller the taproot will be in relation to the diameter of the rootstock.

Multilayered Roots

Interactive growth is characteristic of all multilayered forms but unlike in taproot-forms it is more dependent upon changes in site and orientations of roots. The multilayered form develops from the replacement of one group of roots by another (cf. Veščikova 1964).

Tree VIII (Figure 15B) is an example. As a whorl of laterals replaced the lateral roots below, the upper roots grew more rapidly and became larger than the roots below; this replacement occurred six times. However this type of growth depends upon the rootstock being completely surrounded by lateral roots and the lower roots being unable to continue to grow.

In Tree VII (Figure 13) the replacement of one whorl of roots by a whorl above was not complete as in Tree VIII (Figure 14). This resulted in large roots occurring in both the upper and lower whorls. The infralateral L, the largest root developed before the 10th year, maintained a direct connection with the trunk between the supralaterals B and I. It was not suppressed in any way.

STRUCTURE OF ROOT SYSTEM AND TRUNK GROWTH

The structure of the root system has many relationships with growth of the trunk. Two of these, the chronological development of roots and interactive growth among roots within a system are examined. Since the root systems are taken from a wide variety of sites, only qualitative comparisons of trees are possible.

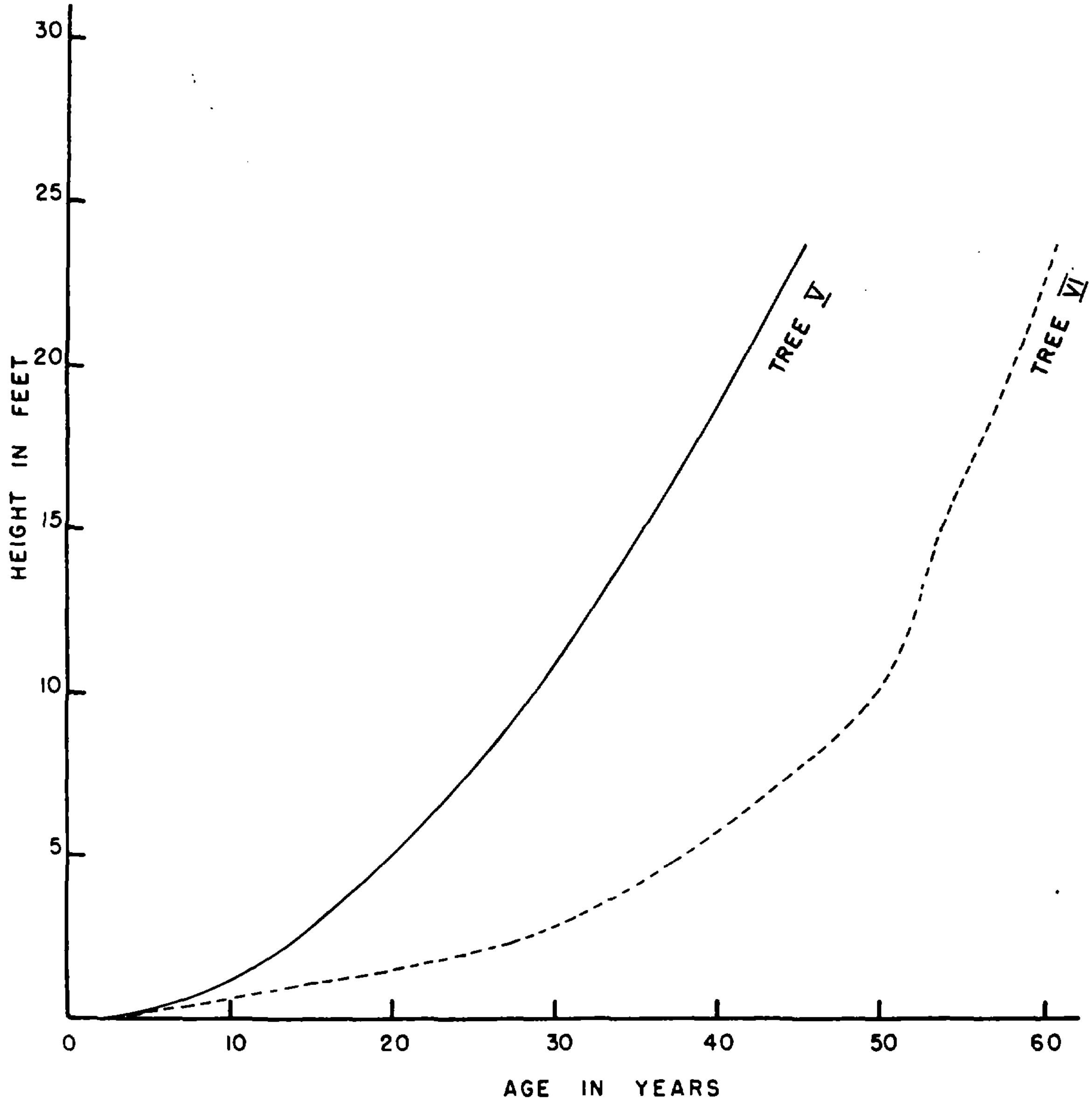

Figure 21. Differences in height growth and age between Tree V, which established roots at an early age, and Tree VI, which established roots at a later age.

Tree VIII (Figure 22). This variation in height increment must be accounted for partially by differences associated with the established root systems.

The replacement of one system of roots with another does not appear to be consistent with maximum growth although, on some sites, this is the only way a tree can maintain itself. The trunk growth of a tree with a young expansive root or one with an older decadent root does not equal the growth of one with an old established root. A replacement of roots leads to a fairly uniform rate of trunk increment.

Four root-forms are found in the region.

The elongated taproot-form occurs on well-drained Podzolic soils where taproot growth is not restricted by soil texture, structure or drainage. The taproot maintains a direct connection with the trunk through a gap between the laterals at the rootstock. Usually the elongated taproot consists of primary roots since it is found on soils with a thin L-H layer in which secondary roots do not develop readily.

The restricted taproot-form, which occurs on well-drained Podzolic, Regosolic and Solonetzic soils, has several origins. The growth of the taproot and proximal roots may be aborted and contorted by textural changes between horizons or restricted by compaction of the underlying soil. The taproot may be restricted by rapid development of a complete whorl of secondary lateral roots around the rootstock. A contorted variant occurs early in growth through horizontal orientation of the taproot in decayed logs, humus and wet soils. Restricted taproot-forms are composed of both primary and secondary roots.

The monolayered root-form, with or without a vestigial taproot, is found in imperfectly-drained to poorly-drained Podzolic and Gleysolic soils. The lateral roots form a single whorl around the rootstock; sometimes a partial second whorl exists (bilayered form); and the taproot is vestigial or overgrown in the rootstock. The form may develop from an aborted or degenerate taproot in the seedling, from restriction by a rock or gley layer, or from degeneration of the lower part of the root system in the presence of a fluctuating water table. The root system, depending on the mode of development, consists of either primary and secondary roots or all secondary roots.

The multilayered root-form is common on well to imperfectly-drained Regosolic soils and very poorly-drained Gleysolic soils. The well-developed form occurs in the presence of thick lacustrine and alluvial deposits. The form develops on sites where the water table is rising or soil frost is rising, accompanied by growth of moss and humus accumulation. Poorly-developed forms that grade into the monolayered root-form are found on poorly-drained Podzolic soils with a thick feather moss and humus layer. Development of the multilayered form is dependent upon the formation of secondary roots, and all large roots are of secondary origin.

Variations of the typical root-form can be found on any area; these result from the spatial organization of roots during morphogenesis. Differences in the orientation of seedling roots in the rooting medium (a mechanical influence) and the interaction of growth among roots (a physiological influence) produce variations of form.

Two variants of the multilayered form resulted from a retardation of growth of primary roots by a decayed log and from two different and opposite (complex) changes in site. A monolayered form of primary roots instead of secondaries developed in sphagnum because of elevation above the general soil level. Interactive growth, occurring in all root systems, is qu'un jeune plant; elle peut aussi avoir sa source dans la présence d'une strate de roc ou de gley près de la surface, ou dans la dégradation de la partie inférieure du système radiculaire à cause de la présence d'une nappe phréatique fluctuante. Dans cette forme, se rencontrent soit des racines primaires et secondaires, soit uniquement des racines secondaires, selon le mode de développement qui existe.

Enfin, la racine multifasciculée est fréquente dans les sols régosoliques mal drainés et dans les sols gleysoliques mouillés. C'est dans les épais dépôts d'alluvions ou lacustres qu'elle se développe bien, plus particulièrement aux endroits où la nappe phréatique a tendance à s'élever et où le sol gèle plus profondément qu'auparavant; de tels endroits sont couverts de mousse et d'humus. Les formes intermédiaires (entre la racine multifasciculée et la racine fasciculée) arrivent en des sols podzoliques mal drainés couverts d'une épaisse couche d'humus et de mousse. Toutes les grosses racines de cette forme générale sont d'origine secondaire.

Les racines de chaque forme générale se trouvent dans chaque Station: leur formation dépend du lieu précis où elles poussent. Au nombre des diverses influences, signalons l'orientation des racines des jeunes plantes dans le sol (c'est une influence mécanique); signalons aussi l'interaction des racines au cours de leur croissance (influence physiologique).

Parmi les variétés de racines multifasciculées, l'une résulte du retard dans la croissance des racines primaires causé par un tronc de bois pourri gisant; l'autre a pour origine la présence de sol différent et complexe situé dans le chemin des racines. Une racine fasciculée à membres primaires (sans racines secondaires) se développait dans la tourbe à sphaigne qui s'élevait au-dessus du sol adjacent. L'interaction de la croissance, présente dans toutes les formes, est plus prononcée lorsque la forme évolue, au cours de son développement morphologique, en une racine soit multifasciculée ou pivotante réduite.

La forme qu'adopte la racine influe sur la croissance du tronc: celle-ci est retardée aussi longtemps que prennent les racines pour bien se développer. Ce cas est le plus évident lorsque la racine devient multifasciculée: pendant qu'un nouveau fascicule de racines latérales se forme pour remplacer celui qui se dégrade, le tronc croît à un taux comparativement plus lent, bien que régulier.

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APPENDIX 1

Scientific Names of Trees, Plants and Mosses*

Alpine fir	*Abies lasiocarpa* (Hook.) Nutt.
Aspen	*Populus tremuloides* Michx.
Balsam poplar	*Populus balsamifera* L.
Black spruce	*Picea mariana* (Mill.) BSP.
Bog cranberry	*Vaccinium vitis-idaea* L. var *minus* Lodd.
Canadian buffalo-berry	*Shepherdia canadensis* (L.) Nutt.
Bunchberry	*Cornus canadensis* L.
Cladonia	*Cladonia* spp.
Creeping juniper	*Juniperus horizontalis* Moench
Dahurian larch	*Larix gmelini* (Rupr.) Litvin
Dwarf birch	*Betula glandulosa* Michx.
Feather moss	*Hylocomium splendens* (Hedw.) BSG.
Fireweed	*Epilobium angustifolium* L.
Kinnikinnick	*Arctostaphylos uva-ursi* (L.) Spreng.
Labrador tea	*Ledum groenlandicum* Oeder
Meadow horsetail	*Equisetum pratense* Ehrh.
Mooseberry	*Viburnum edule* (Michx.) Raf.
Norway spruce	*Picea abies* (L.) Karst.
Paper birch	*Betula papyrifera* Marsh.
River alder	*Alnus tenuifolia* Nutt.
Sedge	*Carex* spp.
Sphagnum	*Sphagnum* spp.
Stiff club-moss	*Lycopodium annotinum* L.
Tamarack	*Larix laricina* (Du Roi) K. Koch
Twin-flower	*Linnaea borealis* L. var *americana* (Forbes) Rehd.
White spruce	*Picea glauca* (Moench) Voss
Willow	*Salix* spp.
Woodland horsetail	*Equisetum sylvaticum* L.

* Taken from: Moss, E.H., Flora of Alberta. University of Toronto Press, Toronto, 1959.

Tree VI (Figures 11, 12C, 21)

The tree, 60 years old, 23.1 feet high and 3.9 inches d.b.h., grew in a pure stand of white spruce south of Grande Prairie, Alberta. The feather mosses, *Hylocomium splendens* and *Pleurozium schreberi*, were dominant under the trees, and willow, mountain alder and grasses were in the openings. The very poorly-drained Gleysolic (Orthic Humic Gleysol) soil, having a 5-inch L-H horizon of feather moss and humus, 6-inch Ah and a gleyed B horizon at 11 inches, developed on glacio-lacustrine clay.

Tree VII (Figures 13, 15A)

The tree, 35 years old, 18.0 feet high and 2.5 inches d.b.h., grew in a sparse stand of black and white spruce near Fox Creek, Alberta. The vegetation was paper birch, Labrador tea, grasses, bunchberry and twin-flower. The very poorly-drained Gleysolic (Peaty Rego Humic Gleysol) soil, formed on lacustrine clay, had a 6-inch L-H horizon of sphagnum and decomposed peat and a 4-inch Ah which was underlaid with gley.

Tree VIII (Figures 14, 15B, 22)

The tree, 88 years old, 32.9 feet high and 4.1 inches d.b.h., grew in a dense stand of white and black spruce and tamarack on a high terrace near the mouth of Hay River, Northwest Territories. The vegetation was paper birch, sedge and an almost continuous carpet of feather mosses (*Hylocomium splendens, Pleurozium schreberi* and *Ptilium crista-castrensis*). The waterlogged Gleysolic (Rego Humic Gleysol) soil, developed on lacustrine sand, had a 5-inch L-H horizon of feather moss and humus and 12-inch Ah underlaid with a mottled C Horizon. Free water was present at the surface in the middle of July.

Tree IX (Figure 16)

The tree, 35 years old, 20.3 feet high and 3.0 inches d.b.h., grew in a mixed stand of balsam poplar and mountain alder on the shore of Great Slave Lake at Vale Island, near Hay River, Northwest Territories. The only vegetation was woodland horsetail. The well-drained Regosolic (Orthic Regosol) soil was coarse lacustrine sand deposited on a levée. The profile showed a 3-inch deposit on a 31-inch deposit both of which overlay a 2-inch humus layer on top of sand.

Tree X (Figures 17, 19A)

The tree, 33 years old, 23.7 feet high and 3.4 inches d.b.h., grew in a dense stand of white spruce on the Simonette River south of Valleyview, Alberta. The ground cover was willow, stiff club-moss, mooseberry, twin-flower, grasses and feather moss. The well-drained Podzolic (Bisequa Gray Wooded) soil, developed on very fine aeolian sand, had a 6-inch decayed log on top of a 3-inch Ae, 6-inch Bf and a deep C/B+ horizon.

Woody Plant Roots Fail to Penetrate a Clay-Lined Landfill: Management Implications

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ABSTRACT / In many locations, regulatory agencies do not permit tree planting above landfills that are sealed with a capping clay, because roots might penetrate the clay barrier and expose landfill contents to leaching. We find, however, no empirical or theoretical basis for this restriction, and instead hypothesize that plant roots of any kind are incapable of penetrating the dense clays used to seal landfills. As a test, we excavated 30 trees and shrubs, of 12 species, growing over a clay-lined municipal sanitary landfill on Staten Island, New York. The landfill had been closed for seven years, and featured a very shallow (10 to 30-cm) soil layer over a 45-cm layer of compacted grey marl (Woodbury series) clay. The test plants had invaded naturally from nearby forests. All plants examined—including trees as tall as 6 m—had extremely shallow root plates, with deformed tap roots that grew entirely above and parallel to the clay layer. Only occasional stubby feeder roots were found in the top 1 cm of clay, and in clay cracks at depths to 6 cm, indicating that the primary impediment to root growth was physical, although both clay and the overlying soil were highly acidic. These results, if confirmed by experimental research should lead to increased options for the end use of many closed sanitary landfills.

Restrictions on Use of Woody Plants on Closed Landfills

Modern landfill technology includes methods for isolating landfill contents, largely to prevent wetting of the contents and subsequent pulses of leachate that might contaminate surrounding lands and waters. This is accomplished by sealing the top of a completed landfill with an impermeable liner, using one of two methods. Either a thick layer of dense clay is spread over the top and sides of the mounded trash, or the mound is carpeted with a synthetic waterproof fabric (a goetextile). Both types of linear are covered with a layer of soil, which is designed to function as a combination barrier protection layer, drainage channel, and growth medium. Both systems are engineered to function for several decades, during which time landfill contents are expected to slowly decompose anaerobically (Anonymous 1980, Lutton 1982, Oweis 1989, Miller 1988, Woodward 1989).

Given their constant shifting and settling, closed landfills are often unsuitable for building construction, and options are limited to their end use (e.g., Aplet and Conn 1977). Therefore, the main defining feature of many closed landfills, other than shape and size, will be their vegetative cover. Although the soil materials used for final cover, including surface layers, are designed primarily for containment, most sites can accommodate a variety of plant communities, if provided sufficient soil cover (Carnell and Insley 1982, Bradshaw 1984). Typically, however, the vegetation is engineered to match the site, rather than the reverse. Part of the reason for this approach lies with fears that some types of vegetation might interfere with containment. In cases where final cover includes synthetic geotextiles, that concern has been somewhat alleviated by tests demonstrating that those materials are resistant to penetration by tree roots (Landreth 1991, Dobson and Moffat 1993). However, on clay caps, landscaping materials are often restricted by law to herbaceous plants (e.g., grasses and wildflower mixes), out of concern for potential damage to clay barriers posed by woody plant roots.

The origin of those concerns is not clear, although they are expressed in regulations and technical guidelines (e.g., Anonymous 1989, 1991, 1992, citations in Dobson and Moffat 1993). It is not even clear that herbaceous plants should be any less threatening than trees and shrubs. For example, roots of native bunch grasses from the Great Basin of western North America are known to reach depths of several meters (Weaver 1920) in their native soils. Indeed, studies of clay-capped landfills in Wisconsin, USA, indicate that

KEY WORDS: Clay liner; Environmental regulation; Restoration ecology; Root penetration; Sanitary landfills; Woody plants

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grass roots may penetrate clays that are not properly compacted (Grefe and others 1987, cited in Dobson and Moffat 1993). At the heart of the issue, however, is a serious environmental responsibility—preventing contamination of adjacent water tables by landfill leachate. Roots penetrating clay liners could have several conceivable detrimental effects. The most obvious threat would be the creation of a porous liner by vertically piercing roots. Two less obvious possibilities are: (1) drying of the clay liner (with subsequent shrinkage and loss of elasticity), from evapotranspiration conducted through partially penetrating roots; and (2) damage to the clay liner (tearing and exposure), due to windthrow of trees with roots growing in the clay. We have so far found no evidence, direct or indirect, to support any of these concerns or the regulations they have inspired.

Root Growth and Soil Physical Properties

Woody species can be categorized by different root morphologies, and some species are known to produce deeply penetrating roots, at least in loose, well-drained soils. In extreme cases, root depths for trees and shrubs are measured in meters (e.g., Whittaker and Woodwell 1968, Laycock 1967). However, root growth is plastic and so highly dependent on soil properties that distinctions between species blur (Kozlowski 1971, Harper and others 1991, Dobson and Moffat 1993). For example, red maple (*Acer rubrum*) has shallow fibrous roots in swamp forests, but grows deep "striker" roots on drier upland sites (Hutnik and Yawney 1961). Roots of scrub oak (*Quercus ilicifolia*), growing in the Pine Barrens of southern New Jersey, can be classified into five distinctly different morphologies, each associated with a different set of local soil features (Laycock 1967). In many instances, root growth depends on soil nutrients, and root architecture may conform to the distribution of soluble nitrogen or phosphorus (Fitter and Strickland 1991). Soil physical resistance, such as the resistance imposed by dense clay, is particularly notorious for directing patterns of root growth (Hermann 1977, Atwell 1993, Dobson and Moffat 1993). It is common knowledge among gardeners and horticulturists that clay soils are problem soils and that the more fine-textured the clay, the lower the likelihood that any plant species will grow deep roots (Materechera and others 1991).

The clays currently used to cap sanitary landfills are required to feature hydraulic conductivities in the range of of 10^{-7} cm/sec, after compaction, i.e., this material is so dense that water moves down through it at rates of about 1 mm/day. Achieving such low conductivity requires a material with small particle sizes and thorough compaction by heavy equipment. To a plant root, this represents enormously dense material, with bulk densities probably well above those at which most root growth has been observed to stop (Hermann 1977, Atkinson and Mackie-Dawson 1991, McMichael and Persson 1991, Atwell 1993). Furthermore, many of the capping materials employed, at least in the New York area, are sulfide-bearing clays, which acidify when oxidized (Kittrick and others 1982, Tedrow 1986). As such, they represent very poor rooting material, irrespective of their physical properties.

Given the clear constraints imposed on root growth in clay, as well as the propensity for roots to avoid inhospitable soil zones, we hypothesized that woody plants would not pose a hazard to landfill clay liners. In this study, we examined the root systems of woody plants growing over a clay cap on a closed sanitary landfill, testing whether their roots had grown into the clay.

Methods

The Brookfield Sanitary Landfill covers 19 ha near the center of Staten Island, New York. Filling ended in 1985, when the landfill was permanently closed, and a final cover was installed on the most recently filled portion (approximately half the site). This cover consists of a very shallow soil (30 cm or less), as a growing medium, over a 45-cm layer of barrier clay. The soil is a mixture of various shales and tills that were transported to the site from construction excavations. The clay is a pyritis grey marl [Woodbury series, mined in central New Jersey (Tedrow 1986)], graded and compacted to feature an average hydraulic conductance of 10^{-7} cm/sec. During the seven years since closures, a sparse stand of woody plant species has begun growing on the landfill, despite the meager soil. These plants presumably arrived via natural colonization from a surrounding native woodland (Figure 1). The volunteer trees and shrubs were growing at very low densities (145 stems/ha), and ranged in size from about 1 m to over 6 m. Because the above-cap growing medium was so shallow, the site offered an excellent opportunity to examine whether woody plant roots could or would grow into a clay liner. Contact between roots of many of the older trees and shrubs and the barrier clay had probably begun soon after the final cover was applied, and we could examine the results after several years' growth under near-experimental conditions. The final cover on this site will soon be improved, to conform with new, more

Figure 1. Field level photograph of a portion of the Brookfield Landfill, taken in June 1993. The large trees in the foreground are black locust, *Robinia pseudoacacia*.

stringent standards, and we were granted permission by the New York City Department of Sanitation to excavate the woody plants on the site.

In fall 1992, we excavated 30 trees and shrubs, of 13 species, that had been growing for up to seven years. For the most part, they represented the largest specimens available, but some species were represented by a single individual. Species with small, short-lived stems (e.g., blackberries, *Rubus* spp.) were excluded. For each plant sampled, we chopped through the main lateral roots in a circle of 1–2.5 m diameter (depending on plant size), removed surface soil from around the attached roots, dug out the exposed root mat, and tipped the plant on its side. Within the area excavated, any remaining soil was scraped to expose the clay cap, which was examined for the presence of plant roots, living or dead. Maximum root depth of the excavated plant was measured, as well as the overburden soil depth, and the maximum diameter of the largest exposed root. Each plant was aged by counting growth rings, and each plant's size was determined by measuring basal stem diameter and height from soil surface to the tallest growing bud. To estimate potential physical resistance to root growth in both soil and clay, probes were made with a spring-type penetrometer (Soil Test Incorporated Pocket Penetrometer), which provides a relative measure of resistance to a calibrated force (McKyes 1989, Bengough 1991, Campbell and O'Sullivan 1991). All probes were made in the field following a rain, in order to obtain moist soil conditions. Beneath each plant, 250-cc samples of soil overlaying the clay cap were removed for laboratory pH tests, using a laboratory electrode inserted in a slurry of homogenized soil and distilled water (McLean 1982).

Results

Nineteen species of woody plants were found growing on the landfill; 13 had sizable individuals living above the clay cap. Judging from their ages, many of the sampled trees and shrubs had begun growing on the site soon after the cap was installed. All 30 plants examined, including the largest, had extremely shallow root plates (Figure 2). Tap roots of all sizes were deformed in many cases (Fig. 2C,D), growing entirely above and parallel to the clay layer. A few small feeder roots were found in the top 1 cm of clay, and in several cases, in cracks at depths of up to 6 cm, but no significant penetration of the clay cap was observed. Maximum root depth was typically equivalent to the depth of the soil overlying the clap cap (Table 1). Despite the very shallow soils, many of the plants were not particularly small for their ages and were apparently able to maintain sizable root volumes that spread well beyond the canopies.

Soil pH beneath each specimen was substantially higher than that of the underlying clay (4.0 vs 3.1, on average), although values for the soil were themselves quite low, perhaps due to acidification by the clay cap (R. Duell personal communication). Mean penetrometer resistance measurements were 0.54 MPa for the soil and 2.36 MPa for the clay. Values for the clay increased with depth, and measurements taken at depths >10 cm were off the scale of the instrument, >3.10 MPa. Values above 2.0 MPa indicate strong potential root impedance (Glinski and Lipiec 1990,

Figure 2. A. Side view, excavated root plate of a 6-yr-old black locust growing in 20 cm of soil above a clay cap. The tip of the shovel rests on the surface of the barrier clay. B. Frontal view of root plate in A. Note the large (8-cm-diam.) tap root that has grown horizontally (arrow). C. Roots of a 4-yr-old grey birch, *Betula populifolia*, that was growing in a small depression. Note that lateral roots (on left) have curved upward, remaining above the clap cap. D. Detail of root growth in a 5-yr-old groundsel bush, *Baccharis halimifolia*. Note the abrupt curvature in the tap root (arrows), which occurred at the soil–clay interface.

Ch. 4, Bengough 1991, Campbell and O'Sullivan 1991).

No damage to the barrier clay cap by woody plants was observed. The plants examined represent a wide array of potential root growth forms, yet all remained above the liner. Bayberry (*Myrica pensylvanica*), for example, is capable of growing very deep lateral roots (Laycock 1967), and both black cherry (*Prunus serotina*) and pin oak (*Quercus palustris*) can produce tap roots that penetrate well over 1 m (Hough 1960, Kozlowski 1971). In all cases, only minute feeder roots were found in the topmost part of the clay. Even for trees as tall as 6 m, the root mass remained shallow, spreading laterally, rather than downward.

Discussion

Root Growth and Soil Physical Properties

Given evidence from previous research on root–soil interactions, we anticipate that our results are in-

Table 1. Measurement data from 30 excavated trees and shrubs growing over a clay liner on Brookfield Landfill, Staten Island, New York[a]

Species	Common name	Height (cm)	Basal diam. (cm)	Age (yr)	Soil depth (cm)	Root depth (cm)	Root diam. (cm)	Soil pH	Clay pH
Tree species									
Betula populifolia	grey birch	170	2.5	4	8	8	2.5	3.41	2.84
		505	15.0	6	10	10	7.0	3.14	2.52
		400	8.0	5	12	15	4.0	3.41	3.14
Liquidambar styraciflua	sweet gum	380	8.0	5	17	21	2.5	3.60	3.20
Morus sp.	mulberry	310	8.0	7	35	35	4.5	5.13	3.12
Prunus serotina	black cherry	175	4.0	6	19	15	3.5	4.09	3.47
		210	3.5	7	20	15	3.0	4.01	3.32
		440	22.0	7	12	13	13.0	3.97	3.16
		393	12.0	7	20	21	7.0	3.70	2.73
		235	4.5	7	14	14	4.0	3.71	2.91
Quercus palustris	pin oak	245	6.0	5	19	20	5.0	3.53	3.03
Robinia pseudoacacia	black locust	360	8.0	6	20	21	8.0	3.84	2.90
		410	10.0	5	14	14	6.0	3.70	3.00
		405	6.0	4	24	24	4.0	4.72	2.96
		627	12.0	7	20	20	7.5	4.75	2.76
		533	11.0	7	33	28	6.0	4.10	3.70
Shrub species									
Baccharis halimifolia	groundsel bush	130	2.0	5	21	21	1.5	4.33	3.64
Cephalanthus occidentalis	buttonbush	125	4.5	5	21	21	2.5	3.72	3.01
Myrica pensylvanica	bayberry	115	2.0	5	25	17	2.0	4.32	3.56
		135	2.5	6	25	18	2.0	4.28	3.46
		110	2.5	5	18	18	2.0	4.90	3.19
		141	2.0	3	21	22	1.5	4.00	3.08
		107	1.5	3	20	21	1.0	4.97	2.67
Rhus glabra	smooth sumac	136	2.0	7	19	17	1.0	4.41	3.11
		235	3.0	7	17	13	1.0	4.32	3.05
		240	3.5	7	15	10	1.5	3.29	2.89
		167	1.0	6	22	17	1.0	3.72	3.18
		145	1.0	5	34	15	1.0	4.17	3.15
Sambucus canadensis	elderberry	195	2.0	5	24	26	1.5	3.86	2.83
Viburnum dentatum	arrowwood	200	3.0	6	35	29	2.0	3.73	2.65
Means		266	5.8	5.7	20.5	18.6	3.6	4.03	3.08

[a]Soil depth represents only the amount of cover material above the clay at each sample location.

dicative. Studies of root growth in heavy soils indicate that the types of clay used to seal landfills, with their high bulk densities and small pore sizes, will be impervious to plant roots, including those of woody species (Russell 1977, Ch. 8, Klepper 1987, Bennie 1991, Materechera and others 1991). In order to grow, a root must push aside soil particles or else work through soil pores, cracks in rocks, or other discontinuities. Whereas an extending root tip has a diameter of 0.1–3 mm, soil pore diameters range from 0.002 to 0.2 mm, with even lower values for pure clay (Taylor 1971, Rendig and Taylor 1989). Dense soils, with their small average particle size—especially compacted clays—represent strong barriers to root penetration, because the small pores are rapidly clogged with fine particles that accumulate around the root tips (Dexter 1986, Greacen 1986, Atwell 1993). The forces necessary to penetrate such soils are beyond the capability of most plants studied. Root tips of any plant species extend by cell enlargement, driven by turgor (osmotic–hydraulic) pressure, and there are absolute limits to the amount of force that can be generated under these circumstances (Dexter 1987, Glinski and Lipiec 1990, Whalen and Feldman 1990, Atkinson and Mackie-Dawson 1991). Tree roots are notorious for breaking pavement and cracking rocks, but this activity is driven by gradual increases in girth of roots already in place, not penetration by young, growing root tips (Hermann 1977).

Further Research Needs

Although our field data seem clear and consistent, additional experimental information is needed for three reasons. First, the duration of growth was short, relative to the life-span of the plants examined and the effective life-span of a typical clay barrier cap. Second, a limited number of species was examined, simply because no others were available. Third, no controls (i.e., specimens growing on more natural soils) were examined to compare root growth off the cap during the same time period. To expand our empirical data base, we have begun a more stringent experimental test, using 17 tree and shrub species with a range of observed root morphologies, planted on and off clay-capped landfills, designed to directly test the three concerns presented above. While these experiments will continue for some time, preliminary results are consistent with those described in this paper.

We did not specifically test for the mechanism of root inhibition. Because these types of clay caps are not only nutrient-poor, but can inhibit nutrient uptake (by acidifying the root–soil interface), root growth into clay caps (especially pyritic clays) could be impeded chemically, as well as physically. Furthermore, dense clay soils are low in oxygen, and many species do not tolerate strongly anoxic rooting zones (Russell 1977, Ch. 9). We did find that some roots grew a very show distance into the clay. It is not clear whether they stopped penetrating due to physical or chemical inhibition or oxygen deficiency. Because the overlying soils had low pH values themselves, we suspect that the primary inhibition was not acidity. However, any of these factors might have acted independently or operated in combination to impede root growth.

Management Implications

Regulations that prohibit woody plants on clay-capped landfills illustrate a conflict between the short-term need to address environmental concerns and a long-term need for comprehensive landscape planning. On the one hand, minimizing leachate contamination protects nearby soils and waters, and any real or imagined risk is magnified by the strength of this concern. However, many landfills, like other degraded sites, are extremely unappealing landscape elements that detract from their urban or rural surroundings. If they are simply maintained for decades as mowed grassy mounds—which typically revert to weedy wastelands (Stalter 1984, Robinson and others, 1992)—then their continued presence is a long-term detriment for human and wildlife populations.

In addition to improving habitat quality and aesthetic properties by increasing vegetation complexity (Robinson and Handel 1993), woody plants could themselves contribute to cap integrity, by reducing soil erosion. For most tree species, the great mass of woody plant roots (ca. 95%) is concentrated in the very topmost soil layers (Lyford 1975, Perry 1982, Watson 1982), at depths well above the limits of the recommended 60-cm minimum soil cover that accompanies a properly installed clay liner (Dobson and Moffat 1993). With their soil-binding capability, woody plants can hold precious topsoils, while maintaining structural integrity, as well as vegetative cover, on closed landfills. With respect to leachate reduction, trees and shrubs remove large quantities of water from soil, and are capable of doing so quickly and efficiently. For example, in experimental plantations on uncapped landfills, trees greatly reduced leachate volume, removing soil water via evapotranspiration (Molz 1977, Ettala 1987).

Nevertheless, with environmental planning focused almost exclusively on waste containment, the potential for promoting ecological complexity in the end-use plans of landfills has been stymied. By limiting approved vegetation to herbaceous plants, regulators allow only a very narrow range of landscaping alternatives for landfill owners and managers. Options for end uses of landfills could be greatly expanded by a careful reassessment of current landscaping restrictions, including those that disallow native woodland development.

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STANDARDIZED PROCEDURES FOR PLANTING VEGETATION ON COMPLETED SANITARY LANDFILLS*

Edward F. Gilman*, Franklin B. Flower† and Ida D. Leone†

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Standardized procedures were developed for those charge with establishing a vegetative cover on completed landfills. Special problems associated with growing plants on these sites are discussed, and step-by-step instructions are given for converting a closed landfill to a variety of end uses requiring a vegetative cover. Procedures are outlined for vegetating landfills with either limited or adequate funds.

Key Words—Landfills, reclamation, vegetation, soils, grasses, woody vegetation, erosion, irrigation, mycorrhizal fungi, root systems.

1. Introduction

Completed landfills throughout the U.S.A. are being developed into parks, golf courses, nature areas and other multiple-use facilities. A critical factor in achieving one of these end uses is establishing and maintaining an effective vegetative stand on the final cover soil. Standardized procedures for planting vegetation on completed sanitary landfills have been developed and are outlined here in step-by-step procedures that are to be followed in sequence. Instructions are included for vegetating a completed landfill with either limited or adequate funds. Although these instructions refer specifically to the U.S. State Agricultural Experiment Stations similar services are available in many other countries.

Data were collected from more than 60 site visits in 21 states (Flower *et al.* 1981; Leone *et al.* 1979), other field experiences, textbooks and standard references on the growth of plants under adverse conditions.

2. Vegetating landfills with limited funds

2.1. *Step A1: selecting an end use*

The end use for a landfill is largely dictated by local needs and the political community. The selection should take place as soon as possible to expedite completion of the project. Each of the following steps will be much easier once a plan is formulated. If funds are limited, the plan might include a passive park, a hunting ground, or a natural open space with trees, shrubs, and grasses. Golf courses, multiple use parks, and other highly intensive recreational uses would require greater expenditures. If an end use has not been selected, controlling erosion will be the primary short-term goal (see Section 2.3., Step A-3).

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*Based on Gilman *et al.* 1983.

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2.2. *Step A-2: determining depth of cover*

The amount and quality of soil cover on a landfill is frequently inadequate for vegetation growth, probably because of the high cost and lack of availability of suitable soil. Deficiencies in cover soil need to be corrected before grass or woody vegetation is planted. The cost of covering an entire landfill with enough rich soil for satisfactory tree growth is excessive. Thus enough soil should be present to bring the total depth to 60 cm (not including the gas barrier layer) in all areas except where trees and shrubs will be planted; the latter areas require at least 90 cm. If portions of the landfill have no cover soil over the final refuse layer, select and spread soil according to steps B-4 and B-5 (Sections 3.4. and 3.5., respectively).

A back-hoe is best suited for determining soil depth, because many holes can be dug in a short time. If this equipment is unavailable, a soil auger and shovel can be used. Because soil depth generally varies over the landfill, several determinations should be made at different points in the area to be planted.

By digging a minimum of 2.5 holes ha^{-1} (one hole per acre) for sites larger than 20 ha (50 acres) 1 hole ha^{-1} for smaller areas, enough data can be collected to determine whether additional soil is necessary, how much is needed, and where it should be placed. The procedures in Steps B-4 and B-5 (Sections 3.4. and 3.5., respectively) should be followed when selecting and spreading additional soil cover.

If results show that more soil is needed anywhere on the site, soil can be moved from one part of the fill to another, or it can be trucked in from another site. Moving the soil is the obvious choice if it can be spared from certain sections. For example, an area that has more than 60 cm of cover soil could supply soil for other parts of the landfill if it is designated for grass and not trees, which require at least 90 cm of soil.

2.3. *Step A-3: establishing an erosion control programme*

2.3.1. *Testing tolerance of ground cover species*

Soil on recently covered landfills must be stabilized immediately to prevent erosion, but soil conditions on landfills make this procedure difficult. Concentrations of CO_2 and CH_4 may be high, O_2 may be low, soil moisture may be limiting, soil is frequently poor quality, compacted soil is common, soil temperatures may be high, and exposures to weather may be extreme.

A one-growing-season study on 1 ha of land should be conducted to select landfill-tolerant grasses. Conditions on such plots must represent those expected over most of the fill area if results are to be meaningful. Conditions to consider include (1) cover soil depth, type and compaction; (2) soil gas concentrations; (3) refuse type, depth, age and compaction; and (4) surface aspect and slope.

Soils in the experimental plots should be tested for pH, Mg, Ca, P, K, NO_3, NH_4, conductivity, Cu, Fe, Zn, Mn, particle size distribution, bulk density and organic matter. Four to five samples should be collected per acre. Step A-4 (Section 2.4.) gives the details on collecting these samples. Soil tests should be performed by the State Agricultural Experiment Station or other certified soil testing laboratory to indicate whether amendments and/or conditioning is required for acceptable seed germination and growth. These amendments should be applied according to soil test recommendations and mixed into the top 15 cm before the plot is seeded.

Each test area should be divided into at least three blocks, and each block should be planted with all the species being evaluated in 9- to 18-m^2 plots delineated by string. This procedure will provide three replications of every species in each area. The species should be randomly distributed within each block. Hand seeding will be necessary. Twenty or more species can be easily handled in this manner.

Seed companies and the State Agricultural Experiment Station are likely to cooperate in selecting species with which to experiment. In most cases, seed varieties should be chosen to accommodate very dry sites and the cover soil conditions particular to the landfill (these should be checked by testing the soil as in Step A-4, Section 2.4.). Species selection may require more care on fills with a known end use, since aesthetics and compatibility with the use must be considered along with erosion control. A list of species recommended for strip mines or other difficult-to-reclaim areas appear in Table 1.

TABLE 1

Some grasses and legumes that should be tested for landfill adaptability*

Grasses	Legumes
Kentucky 31 *Festuca arandinacea*	Crownvetch *Coronilla varia*
Perennial ryegrass *Lolium perenne*	Birdsfoot trefoil *Lotus corniculatus*
Weeping lovegrass *Eragrostis curvulara*	Alfalfa *Medicago sativa* (Lucerne)
Millet *Echinochloa* spp.	Lespedeza *Lespedeza spp.*
Reed canary *Phalaris arundinaces*	Flatpea *Lathyrus*
Switchgrass *Panicum virgatum*	
Orchard grass *Dactylis glomereta*	

*Reference: Vogel 1981.

Seed should be sown in the fall, preferably, or in the very early spring if necessary. The seeding rate varies with the species and can be suggested by the supplier. Seeding rates recommended for landfills are generally several times those recommended for undisturbed lands. Several legumes should be tested along with the grasses, since they are widely adaptable, require less nitrogen for growth and are often used for reclamation.

Mixtures of annuals and perennials are best suited for stabilizing soil and preventing erosion on reclaimed strip mines. The annuals provide a quick temporary cover that is succeeded by the more permanent perennials. Recommended seeding rates should be followed carefully for the quick cover species to prevent dense stands that prevent or retard establishment of the permanent species.

If it becomes necessary to cover portions of the landfill with soil-holding grasses before the experiments have been completed, then the country agricultural agent or soil conservation service can supply the standard seeding and feeding rate (based on the soil analysis outlined in Step A-4, Section 2.4.) for the area for the species selected from Table 1 or otherwise recommended by the county agent.

Some seed mixtures suited for erosion control and site stabilization are not compatible with other land uses. For example, *Sericea lespedeza* and flatpea are excellent for long-term erosion control, but their value as forage and wildlife habitat is lower than that of other legume species. Species should thus be selected for their suitability for the approved land use as well as for their ability to control erosion.

2.3.2. *Planting procedures*

To prevent erosion, steep, sloping ground should be microterraced before seeding by running a wide-tracked bulldozer up and down the slope without touching the blade to the soil. The seed should be handspread and raked into the soil. A mulch and asphaltic tack should be applied to hold the seed in place and to conserve soil moisture. Some of the annuals can be seeded in the spring and used as mulch for a fall perennial planting.

Growth on the site should be evaluated once a month by a qualified specialist during the first 4–6 months after germination.

If the plans for a site include a natural area, consider testing any volunteer species already growing at the site. These experiments should begin in the fall so that the following three steps can be implemented during the next summer and planting can be done over the entire landfill in the following fall.

2.4. *Step A-4: determining the soil nutrient status*

2.4.1. *Sampling procedure*

Soils should be tested before or during the grass and groundcover experiments for pH, N_2, K, P, conductivity, bulk density, organic matter, and other macro- and micronutrients mentioned in Step A-3 (Section 2.3.). Soil samples should be collected in a grid or zig zag sample pattern within the proposed planting sites. With homogeneous, single-source soil, one sample for every 2 ha may be sufficient. If a wide variety of cover materials were used, however, more samples are needed. Samples should be collected from a 0–20-cm deep soil column. A composite should be made from five samples. Any number of soil augers or shovels may be used for sampling, but picks and shovels may be needed with very compacted soils. Roots and other plant material should be removed from the sample.

2.4.2. *Fertilizer*

The local country agricultural agent or soil conservation service office may help to collect and analyse the samples, interpret the results and make recommendations for the addition of fertilizer and/or lime. Remember however, that fertilizer may encourage such rapid, vigorous growth of the herbaceous vegetation that the establishment of woody species from seed may be supressed or prevented. Again, such site-specific problems must be worked out with local officials and reclamation specialists.

2.4.3. *Metals*

Soils that contain high concentrations of Zn, Cu, Ma, Fe, Cd or Pb should not be used for cover material unless this situation can be corrected by increasing the pH between 6.5 and 7.0, increasing the P content, or adding organic matter. Studies are available on the relationship of the metal contents of soils to plant growth (Chaney 1973).

2.4.4. *Conductivity*

Conductivity is an important soil characteristic that is frequently neglected in routine

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2.8.1. *Planting*

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analysis. Since salt content can dramatically affect plant root growth and water balance, avoid planting in soils with a conductivity greater than 2 mmohs cm^{-1}. Soils with greater conductivity can be used only after rain water has leached enough salt from the soil to bring it within acceptable limits (i.e. less than 2 mmohs). This process may take several weeks or months, depending on the amount of rainfall and drainage characteristics. Salts may never leach from soils in the drier parts of the country. Conductivity tests can be performed along with the more routine analyses.

2.5. *Step A-5: determining soil bulk density*

Cover soil is frequently compacted by landfill equipment during spreading operations to bulk densities exceeding 2.0 g cm^{-3}. Bulk density can be determined by weighing five to seven undisturbed soil cores of a known volume (e.g. 300 cm^3) for each hectare. If the density is greater than 1.7–1.8 g cm^{-3}, plant root growth will probably be severely restricted. Compacted soil should at least be sacrificed, and organic matter added to enhance the physical properties.

2.6. *Step A-6: amending cover soil*

The soil over the entire planting area should be amended with lime, fertilizer, and/or organic matter according to recommendations from the soils lab one to several weeks before anything is planted. These materials should be incorporated into the top 15 cm of soil.

2.7. *Step A-7: selecting landfill-tolerant species*

From the results of the experimental plots established in Step A-3 (Section 2.3.) grasses and other ground covers can be selected for planting in the soil cover spread on the entire landfill.

2.8. *Step A-8: planting grass and ground covers*

No known studies have been done to define the best planting technique for establishing grasses on landfills, but it is generally desirable to embed the seed in the soil. Mulches have been used as an alternative to embedding the seed, but this approach is less likely to be effective on adverse growing sites such as landfills. On steeper slopes, where embedding or drilling is impossible, a mulch must be used to prevent the surface soil layers from drying out and to hold the seed on the soil until it germinates and establishes a reasonable cover.

2.8.1. *Planting steep slopes*

Several methods exist for dispensing seed onto the cover soil. Steep slopes that are inaccessible to conventional equipment must be hydro-processed in one operation with fertilizer, lime, seed, mulch, and enough tack to hold the mulch on the slope. Hydroseeded soil must not be compacted during spreading and must be very friable at seeding time. Seed will germinate beneath the mulch on hard, compacted soil, but the roots will not penetrate the soil surface and will succumb to drought. Although hydroseeding has been advertised as a miraculous process for vegetating slopes and other areas with adverse growing conditions, results will be disappointing unless the soil is properly prepared with the right equipment at the proper time.

2.8.2. *Planting flat or gently sloping ground*

Many methods exist for spreading fertilizer, lime, seed and mulch on flat and gently sloping ground (hand-spreading, use of cyclone spreader, drilling, furrowing, etc.). The method chosen will be dictated by the soil type and condition, and by other factors particular to the planting areas to be determined by the contractor. To assure that the methods used are suited to the existing conditions, these factors should be carefully studied just before planting.

2.8.3. *Barren areas*

Areas may exist on the landfill cover where plants will not grow because of high landfill gas concentrations. Replanting these areas will generally not eliminate this barren area problem. Wood chips or large stones can be used to prevent erosion and provide an aesthetically pleasing appearance. If gas is extracted or otherwise recovered from the landfill, the ability of the cover soil to support vegetation will be increased. Further discussion of this matter is presented in Step B-2 (Section 3.2.).

If no gas is present in the areas of poor growth, the soil should be checked for the constituents listed in Step A-3 (Section 2.3.) and for erosion washout. If replanting is necessary, the area may first have to be refilled, regarded and microterraced.

2.9. *Step A-9: developing tree and shrub growth*

Efforts to develop a good cover of woody plants should begin by ascertaining that 90 cm of soil is in place in areas where trees and shrubs will be planted. Woody plants generally have a deeper root system and require better anchorage than ground cover species. Soil added to bring the original cover to a depth of 90 cm should be selected and spread according to Steps B-4 and B-5 (Sections 3.4. and 3.5., respectively). If sufficient funds are available, a barrier (Step B-3, Section 3.3.) should be placed beneath each tree-planting area to protect the root system from harmful landfill gases.

The least expensive and most practical means for establishing trees on a completed landfill that has been closed for some time is to plant seeds or small whips of species already establishing themselves on the landfill. Some of these species may be available from the State nursery. Since recently closed portions of landfills and older landfills with very poor cover material are not likely to support many volunteer trees or shrubs, Step B-8 (Section 3.8.), a good reference (e.g. Harlow & Harrar 1969), and/or the county agricultural agent should be consulted to determine which of the volunteer species is best suited for the area.

After the grass has been planted, a 1- or 2-year waiting period is recommended before areas are selected for planting trees and shrubs. If the grass cover with its shallow roots dies or fails to germinate because of the influx of gases from the landfill, it is nearly certain that other deeper-rooted vegetation (trees and shrubs) will not thrive at these locations.

The procedures presented so far represent the bare minimum required for establishing plants on a completed landfill. As the funds for landfill and uses increase, the more sophisticated procedures described in the next section can be used for establishing grass, shrubs and trees.

Because gas migration into the root zone will adversely affect the survival rate of grass, shrubs, and trees, active extraction of gas from the refuse layers is recommended. This procedure, while effective, is expensive. However, if the gas can be sold for its heating value, the cost of the gas-extraction system may be recovered. If this procedure is not practical, consider placing as barriers between the refuse and tree roots to prevent gas migration. These procedures are covered in Steps B-2 and B-3 (Sections 3.2. and 3.3., respectively).

3. Vegetating landfills with adequate funds

3.1. *Step B-1: constructing the landfill*

Developing an end-use plan before construction or close of the landfill will increase the likelihood that a successful vegetation programme can be implemented. Factors to be considered in vegetating a former landfill include refuse age, type, depth and compaction; location of degradable or non-degradable refuse, proportion of refuse to daily soil cover; amount and type of final soil cover; surcharging of refuse with cover material; area climate; final countouring (including maximum slope) and gas extraction.

3.1.1. *Minimizing gas production*

The amount of landfill gas produced during refuse decomposition is generally related to the amount of putrescible or volatile material deposited in the landfill, age and depth of landfill, water infiltration, etc. (Emcon Associates 1980). To minimize gas production, greater quantities of nonputrescibles can be included in the refuse or the ratio of daily cover to landfilled refuse can be increased.

Placing nonputrescibles (glass, plastics, metals, rubber, concrete, etc.) in specific areas to create nonbiodegradable refuse islands may allow plants to grow in areas relatively free of landfill gases. Such a step may also facilitate more efficient resource recovery in the future. Gases may migrate into these zones from areas containing decomposable material, but grass, shrubs, and trees should grow better above these islands.

3.1.2. *Minimizing surface settlement*

Surface settlement may have to be minimized in some areas so that irrigation lines can be installed and maintained to support trees and shrubs. Islands of nonputrescible refuse have minimum surface settlement and can generally support irrigation lines without the constant maintenance required in the areas containing putrescible refuse, where frequent breaks are caused by uneven settlement. Later surface settlement can also be minimized by surcharging the refuse with the soil that will be used as cover material or by filling the area with shredded or baled refuse.

3.1.3. *Final contouring*

Evidence indicates that slopes steeper than 3:1 (horizontal:vertical) inhibit soil stabilization by promoting soil erosion and hindering vegetative establishment.

3.2. *Step B-2: extracting gas*

The most successful landfill-to-park conversions in the coming years will incorporate a gas extraction system in the landfill to reduce the volume of gases escaping into the final soil cover and inhibiting root growth. These systems will be compatible with gas recovery operations and may eventually pay for a portion of park construction and maintenance requirements.

3.2.1. *Induced exhaust systems*

Induced exhaust systems can aid plant growth by reducing the quantity and pressure of landfill-generated gas. The economic value of such a system could end before gas generation ceases, however, and any sudden increase in soil gas content would probably cause severe plant stress.

Patterns of gas contamination may be seen. Methane and CO_2 can migrate from the refuse layers into the cover soil, though such contamination is not uniform over the landfill site. Some areas will contain relatively high CO_2 (up to 25%) and CH_4 (up to 40%) and consequently have low O_2 contents (less than 6%) but some areas may be influenced very little by the underlying refuse.

3.2.2. *Effect of climate on gas production*

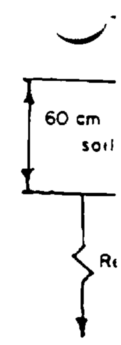
Site visits to some 60 completed landfills within nine major climatic regions of the U.S.A. generally revealed a high negative correlation between plant growth and concentrations of methane and/or carbon dioxide in the root atmosphere (Flower *et al.* 1978). Landfill gas production and vegetation damage varied little among the climatic regions, except that the arid southwest (Arizona) had somewhat lower gas concentrations.

3.3. *Step B-3: selecting gas barriers*

Even with a commercial gas extraction system in operation, special precautions should be taken when planting trees and shrubs. The best procedure would be to cover the entire landfill with an impervious soil layer (Lutton 1980) or synthetic membrane to keep gases from entering the final cover soil. The barrier would also prevent water from infiltrating into the refuse and producing leachate. Gas barriers should at least be installed beneath tree and shrub areas.

A variety of barriers are currently available to control gas migration. A 30–60 cm layer of impermeable clay over the final refuse layer followed by at least 60 cm of fertile soil provides an effective barrier and is known as the mound system. Other successful barriers include polyvinyl chloride, hypalon and other membrane sheeting (greater than 0.5 mm, 20 mils, thick) (Matrecon 1980). Sand layers above and below the membranes provide physical protection during installation. Bentonite has also been effectively used to prevent gas migration into tree and grass root zones. Another effective system is the trench barrier system (a modification of the mound system), which may be useful when soil mounds are not desirable in an area. This system (Fig. 1) has been successful on a small scale (3 × 4 m) (Leone *et al.* 1979) but it would be preferable to secure a barrier all the way to the soil surface to avoid contact of the cover soil with wastes and laterally migrating gases.

A method suitable for planting trees and shrubs in planting islands and parking lots



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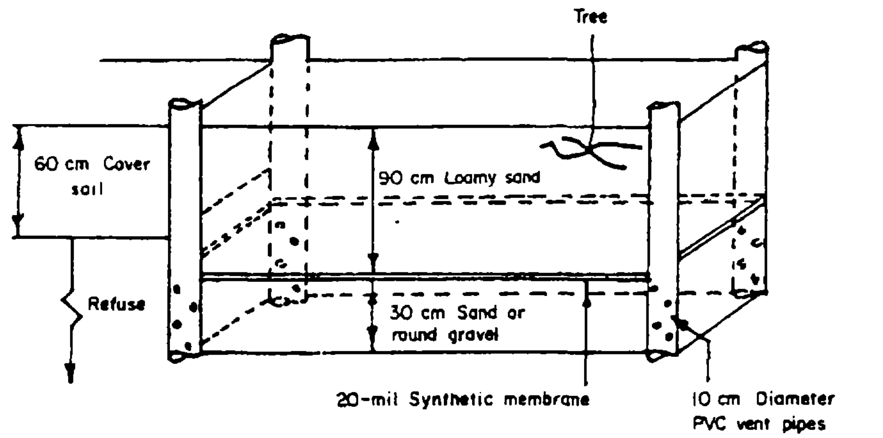

Fig. 1. Trench barrier system for small planters. Vent pipes should be spaced no more than 2 m apart.

involves construction of a saucer lined with an impermeable polymeric membrane and drained by an open U-tube at the bottom of the saucer.

The success of any gas barrier depends on maintaining its integrity. Cracks or breaks in the barrier may result from refuse settling, which may continue for scores of years. Thus gas may migrate into previously uncontaminated areas, and areas containing gas may become free of it.

3.4. *Step B-4: selecting cover soil*

Successful revegetation depends greatly on the final cover soil, which can be costly and difficult to find. Final layers of cover soil should be selected according to the following criteria.

Select a soil with a texture closest to loam for areas containing trees and shrubs. This soil should be tested for the constituents listed in Step A-3 (Section 2.3.). Five composite samples consisting of five subsamples each (Step A-4, Section 2.4.), should be sent to a certified soil testing laboratory. More samples will be needed if a variety of soils are to be used for the cover. Soil should be tested before it is sent to the site since it is relatively easy to amend before or during spreading.

3.5. *Step B-5: spreading cover soil*

Clay soil layers should be over the final refuse layers according to recommendations made by Lutton (1982). The clay barrier layer should be compacted to 90% of maximum dry density according to five- or 15-blow compaction tests. Additional soil for supporting vegetation should be spread as described below.

Actual placement of cover soil is critical. To avoid compaction, which can restrict root growth and contribute to surface water ponding, the following steps should be taken: (1) mix organic matter with the soil before spreading, (2) spread soil when it is dry and (3) use earth-moving machinery other than the normal earthscraper. Dragline excavators, bucket-wheel excavators, forward-acting shovels, and bulldozers have been proposed but may be more costly (McRae 1979).

If several different soils will be used in the final 60–90 cm of cover, they should be mixed together and spread them as units to promote less overall compaction, increased water movement, and better root growth.

If soil must be spread conventionally and bulk densities exceed 1.7–1.8 g cm^{-3} one of several procedures is used to mitigate this effect. Subsoiling or deep time ripping can be used but are not completely effective.

Organic amendments should be made before the cover is spread. They will improve the physical, chemical and biological properties of most cover soils. Organic materials include humus, peat moss, manure, crop residues, food wastes, logging wastes, industrial organics, leaf compost, composted sewage sludge or refuse compost. A soil bulk density of 1.2–1.4 g^{-1} cm^{-3} is desirable, depending on soil texture. Higher density can generally be tolerated in a coarser soil. Gypsum, perlite or vermiculite may also be disced or chiseled into the existing soil at the time the cover is spread.

Physical soil properties can be improved by establishing a grass or ground cover for several years before planting trees and shrubs.

3.6. *Step B-6: determining soil depth*

Bohm (1979) reports that 60–80% of tree roots volume in the forest occurs in the top 20 cm of mineral soil and that most of the fine feeder roots are in the top several centimetres. Roots are likely to be somewhat deeper in more open situations such as parks and golf courses. The remaining portions of the root system are located at varying depths from 20–90 cm, depending on species and soil. Thus the planner should consider spreading 90 cm of soil in those areas where trees are to be planted, as described in Step A-2 (Section 2.2.).

3.7. *Step B-7: locating areas unsuited for tree and shrub growth*

Possible indicators of potentially poor growth sites are dead or no vegetation, anaerobic soil, high soil temperatures, thin cover soil and settled areas.

3.7.1. *Areas without plant growth*

Areas with dead or no plant growth are likely to have high CO_2 and CH_4 concentrations and elevated soil temperatures. Such obviously barren areas should be avoided when selecting sites for trees and shrubs.

3.7.2. *Anaerobic soils*

Vegetation will die if the soil becomes contaminated with the gases of anaerobic decomposition, a situation that may occur only after plants have been well established. To check for anaerobic conditions, direct gas measurements should be made, the soil's physical characteristics should be examined and certain soil tests should be performed.

Direct gas measurements should be made at depths of 30. 60 and 90 cm with an explosimeter (often used by utility companies looking for gas line leaks). Planting is not recommended if any combustible gases are present. Carbon dioxide and O_2 contents of the root zone should also be measured from bar holes with Bacharach Fyrite or other CO_2 and O_2 indicators. A high CO_2 content is toxic to plants and indicates that soils may be anaerobic at times. Even though an area has low combustible

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Physical examination of soils with anaerobic conditions can reveal unpleasant odors and darker, damper and more clay-like (less friable) characteristics than aerobic soils.

Tests of anaerobic soils will reveal generally higher amounts of ammonium-nitrogen and available managanese. Available Fe and Zn may also be considerably higher in soils that have been anaerobic for an extended period.

3.7.3. *High soil temperatures, thin soil cover, and settled areas*

Temperatures in anaerobic soils are frequently higher than in aerobic soil—from a degree or two to 20 or 30°C in extreme cases. The cause is undetermined, but high temperatures may result from microbial activity, chemical reactions, or underground fires.

The amount and quality of soil covering the refuse is frequently inadequate to support vegetation. Such deficiencies may be corrected as outline in Steps A-2, A-4, B-4, and B-6 (Sections 2.2., 2.4., 3.4 and 3.6., respectively).

Settled areas may hinder plant growth because of pooled water in low areas, or they may encourage vegetation in dry areas because of increased soil moisture. Loss of soil refuse through decomposition creates an undulating surface that causes such conditions and may be unacceptable for some uses such as farming or golf courses.

3.8. *Step B-8: selecting tree and shrub material*

The end use for the completed landfill must be known before plant species are selected. Plants should be adaptable to the area and commercially available there. Refuse quality, quantity, age and depth must also be considered along with climate, since these factors interact to form widely different environmental stresses and gas production rates.

Despite these varying factors, trees and shrubs grown successfully on completed landfill sites have a variety of common characteristics (Flower *et al.* 1981, Gilman *et al.* 1981). Factors that must be considered include growth rate, tree size, rooting depth, flood tolerance, mycorrhizal fungi and pathological considerations.

3.8.1. *Slow versus rapid-growing species*

Evidence indicates that slow-growing trees are more tolerant to landfill conditions than rapid growing species. Fast growers generally draw more moisture from the soil and therefore require more irrigation. But faster-growing trees may be more desirable with their more quickly produced vegetative cover, and they will produce more total growth on a landfill than slow growers if they are irrigated during the first 3 years. Growth rates of various U.S. trees are listed in Table 2. More complete lists are available in Pirone (1978) and Fowells (1985).

3.8.2. *Small versus large plants*

Trees planted when small (1 m tall) show significantly better growth on landfills than do those of the same species planted when taller than 2 m, regardless of species. A small tree can adapt its root system to the adverse environment in the cover soil by producing roots close to the surface and away from high gas conditions. By the

TABLE 2
Some slow, moderate and rapid growing tree species found in the U.S.A.

Slow	Moderate	Rapid
Serviceberry	Littleleaf European linden	Summershade Norway maple
Sargent cherry	European white birch	Shademaster thornless honey locust
European hornbeam	October glory red maple	Sawtooth oak
Yellow-wood	Kentucky coffee-tree	Hybrid poplar
Ginkgo	Hackberry	Willow oak
Flowering dogwood	Kwanzan Japanese flowering cherry	Tree of heaven
		Silver linden

time the large trees adjust to the landfill, smaller trees may equal or surpass them. Where trees taller than 1.5 m must be planted, it should be done on a raised bed to provide adequate uncontaminated depth for already developed roots. Larger plant material can be used only if landfill gas is kept from the root system and the plants are well irrigated.

3.8.3. *Volunteer species* ?

Volunteer tree species have not been specifically studied on landfills, but they are generally very adaptable to poor soil conditions and are often the best species for establishing trees in a low public use area of a landfill.

3.8.4. *Natural rooting depth*

Trees and shrubs that enjoy shallow root systems are significantly more adaptable to landfills than species requiring a much depper root system (Table 3). The deeper roots are subjected to higher landfill gas concentrations and lower oxygen levels. Some species can avoid this adverse environment by producing a shallow root system. Several texts show the natural rooting depth of woody species (Fowells 1965; Harlow & Harrar 1969), but these lists are incomplete.

The fact that trees on landfills generally develop shallower roots than nonlandfill trees emphasizes the need for frequent irrigation of landfill soils planted with woody vegetation, especially if the gas is not extracted from the refuse. If landfill gas is kept out of the cover soil, roots should be able to grow deeper. Landfill cover soils also need irrigation because they do not maintain as high a moisture content as soils off the landfill.

TABLE 3
Vertical distribution of tree roots in landfill and non-landfill soil*

	Average depth (cm)	
Species	On landfill	Off landfill
Japanese black pine	7	9
Norway spruce	5	4
Hybrid poplar cuttings	6	13
Honey locust	8	17
Green ash	9	15
Hybrid poplar saplings	9	13

*Species at top of list were more adapted to the landfill than those at the bottom (Gilman *et al.* 1981).

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Crabapple
Virginia pine
Eastern red ceda

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3.8.5. *Flood tolerance*

Our field data show that changes produced by landfill gases in cover soils are similar to those imposed by the flooding of soils, except that the high moisture content is lacking on a landfill. Thus flood-resistant species may do well on landfills only if they are supplied with adequate water. Dry-site species should be planted if water will not be readily available.

3.8.6. *Plant size at maturity*

Trees that are small at maturity should be chosen if cover soils are shallow (30–60 cm), if gas is not extracted from the fill, or if a gas barrier is not installed. Large trees under such conditions run a higher risk of toppling during high winds. Some small trees and shrubs are listed in Table 4.

TABLE 4
Some small trees and shrubs (less than 9 m tall at maturity)

Common name	Latin name
Upright European hornbeam	*Carpinus Betulus* f. fastigiata
Serviceberry	*Amelanchier* spp.
Hawthorn	*Crataegus* spp.
Goldentrain tree	*Koelreuteria paniculata*
Flowering dogwood	*Cornus florida*
Kwanzan cherry	*Prunus serrulata* "Kwanzan"
Black chokecherry	*Aronia melanocarpa*
Common chokecherry	*Prunus virginiana*
American elder	*Sambucus canadensis*
Sawtooth oak	*Quercus acutissima*
Osage-organe	*Maclura pomifera*
Crabapple	*Malus* spp.
Virginia pine	*Pinus virginiana*
Eastern red cedar	*Juniperus virginiana*

3.8.7. *Micorrhizal fungi*

Mycorrhizal fungi associated with plant roots greatly increase water and nutrient uptake by the plants. This symbiotic association has been successfully used in reclamation of coal strip mines and dump sites. Spore- and mycelium-inoculated soil has been tested for its ability to promote mycelium development on trees in landfill cover soil (Telson, Leone & Flow 1980, pers. comm.). Limited experiments show that both forms of inoculation may be used, but that the spore inoculum appears to be more suited to high gas areas. The roots may be inoculated directly just before planting to increase the likelihood of establishing the beneficial mycorrhizal relationship.

3.8.8. *Pathological considerations*

Selection of vegetation should always be based on its ability to withstand attack by diseases or insects. The county agricultural agent or soil conservation service can provide valuable practical information in this regard.

3.9 *Step B-9: planting and maintaining vegetation*

Trees and shrubs survive best if planted in early spring or fall. The Extension Service or Soil Conservation Service can identify which planting time is best for a specific area and species. Planting should not be done during the summer. Plants purchased from a nursery and delivered to the site should be planted as soon as possible. Bare-rooted material can dry out in a matter of minutes if left in the sun. Balled or burlapped material can be left for some time longer, but if must be irrigated within a day or two, depending on the weather conditions. One person should not be scheduled to plant too many trees in one day. The work load should be scheduled so that only the trees that can be planted in a day are present on the site. In the long run, it may be more desirable to schedule a pick-up or delivery on the same day, arrangements should be made for storing the plants in a shaded, preferably cool indoor environment free from wind. Regardless of how the plants are stored or how soon after delivery they are put into the ground, an irrigation truck or other water-supplying vehicle should be made available to deliver 20–30 l of water to each tree at the time of planting.

A planting hole about twice as wide as the root mass diameter and up to 15 cm deeper than the deepest root is well suited for trees and shrubs. Care should be taken to avoid compacting the sides of the planting hole; such a step might promote prolific root growth inside the original hole but inhibit root penetration into the surrounding soil.

Some of the original cover soil should be mixed with some loamy textured material (preferably a highly organic soil) and enough of it spread in the bottom of the hole to make a 15 cm deep layer (a 50:50 mixture is a desirable combination). The main stem of the tree or shrub should be and fill in around the root system until the hole is half filled. The soil is gently pressed down with the sole of the shoe but is *not* packed down. During the backfilling process, the roots must be relocated so that their depth is equal to their original depth in the nursery. The latter can usually be determined by letting the roots hang freely before planting. The roots must not all be compacted at the bottom of the hole, they must be spread out as much as possible. At this point, the soil should be watered so that the entire root system has been moistened. This step may take 5–30 l, depending on tree size. When the water has all soaked into the soil, the rest of the hole is filled with the soil mix and the soil gently pressed down with the foot. A ridge is formed around the stem with an inside diameter about equal to the extent of the root system. This well is filled with water. These simple procedures will retain all possible moisture from rainfall and irrigation and help trees survive through the most critical first season. Mulching with wood chips, bark, sawdust, grass clippings, plant debris or many other materials can help control water loss by reducing weed growth and evaporation from the soil surface around the trees.

The principles set forth above for planting small, bare-rooted trees generally hold for planting older, larger, balled-and-burlapped specimens. We do not recommend planting trees older than 2–3 years or, as mentioned earlier, taller than 1.0–1.5 m with root systems 15 cm or more below the soil surface unless specific provisions for preventing gas migration into the root zone have been implemented and the soil is at least 90 cm deep. If it is impossible to obtain small seedlings for planting, more water must be provided at the time of planting and during subsequent irrigation periods to saturate the soil around the root system. Also, each of the trees must be supported with at least two stakes and preferably three.

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from those for nonlandfill areas, except that additional irrigation is required. Soil with a low nutrient status must be fertilized, and soils with the wrong pH (below 5.5 and above 7.0) must be limed or acidified to desirable limits. The pH and nutrient levels in the soils should be tested periodically (every 2–3 years) after planting. Fall is the best season for such testing so that any necessary soil application can be made in early spring. The county agricultural agent and Step A-4 (Section 2.4.) can provide information on proper soil sampling methods and interpretation of the test results.

Irrigation is an extremely important requirement for establishing and maintaining healthy plant material on former sanitary landfills, particularly during the first 2–3 years after planting. After this time, roots may have been established a large enough system to withstand moderate drought periods; but irrigation should be practiced during extended hot, humid weather even for large, established trees. This additional watering is needed because of the shallow roots close to the landfill soil surface where there is little available soil moisture during extended dry periods. In-ground irrigation systems require continual repair, since settlement is likely to cause frequent breaks in the pipes and thus increase maintenance costs. Various above-ground, expandable-joint irrigation systems are available.

Plants should be protected from disuse and insect infestations and damaging animals. Check with the county agricultural agent and nurserymen to see if the selected species are susceptible to attack. Some species are particularly vulnerable to winter desiccation. The county agent can recommend procedures for overcoming this problem. Excellent instructions for tree maintenance are provided by Pirone (1978).

4. Conclusions

Closing and converting a landfill for useful purposes can be accomplished with either limited or adequate funds. A successful stand of vegetation can be achieved on sites where plant growth has been traditionally difficult or impossible to maintain. The ability to convert sites for recreational and aesthetic purposes is growing in importance as more and more landfills are completed and abandoned.

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loss) indicates a considerable difference in pore size for each phase and suggests that different levels of structural organization are involved. This possibly suggests a basic soil unit composed of many randomly oriented quasi-crystals. Structural phase pores exist between these units and residual phase pores within the units. A similar model has been proposed by A. V. Blackmore (personal communication) and by B. P. Warkentin (personal communication). Certainly any structural model proposed for these soils must satisfy this basic organizational requirement.

ACKNOWLEDGMENT

We gratefully acknowledge many helpful discussions with Dr. D. E. Kissel; encouragement from Dr. W. R. Gardner; the morphological descriptions, sampling assistance, and analysis by the USDA Soil Conservation Service, Soil Survey Division; and general assistance from Mrs. R. E. Yule.

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Soil Shrinkage Relationships of Texas Vertisols: II. Large Cores[1]

D. F. YULE AND J. T. RITCHIE[2]

ABSTRACT

Although soil shrinkage in the field has been related to water content changes, this relationship has not been correlated with small core measurements or defined in terms of structural and shrinkage water loss phases. Since field measurements are limited by the accuracy of the water content determination, undisturbed cores (73 cm diam and 140 cm long) from the eight Vertisols studied previously were studied to accurately measure water loss (by weighing). *Sorghum* plants were established, and a single drying cycle was studied. Vertical shrinkage was measured at the surface and at the 15-, 35-, 55-, 95-, and 115-cm depths, and the water content profile was measured with neutron moisture and gamma density probes. These data were interpreted in terms of the shrinkage pattern found in the cores and with the use of small core data obtained by Yule and Ritchie. (1980).

Although the water loss data were confounded by large soil evaporation from shrinkage cracks at the side of the cores, the evidence suggested that the shrinkage response was a combination of structural and shrinkage water loss phases. Consequently, the shrinkage curve for the soil surface asymptotically approached the theoretical equidimensional, normal curve. Shrinkage curves with profile depth tended to parallel the soil surface curve. The water content profiles obtained were not precise, but shrinkage parameters calculated for various depth increments resembled the small core data obtained previously. The results showed that small core data could be used to predict field shrinkage responses if field soil water content profiles are known.

Additional Index Words: **bulk density, montmorillonite, soil water content.**

Yule, D. F., and J. T. Ritchie. 1980. Soil shrinkage relationships of Texas vertisols: II. Large cores. Soil Sci. Soc. Am. J. 44: 1291–1295.

THE 10-CM CORE EXPERIMENTS (Yule, and Ritchie, 1980) have confirmed the importance of structural and shrinkage water loss phases to the shrinkage behavior of Vertisols at typical field water contents. Few attempts have been made to relate field behavior to these two water loss phases or to use small core data to predict field behavior.

Although it is relatively easy to measure the vertical movement of the soil surface in the field, accurate measurement of volumetric water content change is particularly different because of the effects of cracks. Aitchinson and Richards (1965) suggested that the fractional change of vertical dimension may well be the most valid measure of water content change in heavy clay soils. However, vertical shrinkage is related to water loss only during the shrinkage water loss phase, and any structural water loss occurring in the field would not be measured by this procedure.

Many field measurements have shown that the ratio

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of vertical shrinkage to water loss is 0.33 or less (Woodruff, 1936; Aitchison and Holmes, 1953; Jamison and Thompson, 1967; Yaalon and Kalmar, 1972). Since this ratio for the equidimensional, normal shrinkage water loss phase is greater than 0.33 (Yule and Ritchie, 1980), field data suggest that most water loss occurs in the shrinkage phase with some structural water loss, and, possibly, some residual water loss near the soil surface. However, the precision of the field measurements is not sufficient to delineate the amount of structural water loss.

By comparison, Fox (1964), Swartz (1966), and Berndt and Coughlan (1976) fit data from bulk density sampling at high water contents to a unidimensional relationship (as defined by Fox, 1964). Based on small core measurements, Berndt and Coughlan (1976) suggested that the field relationship may be an artifact of the technique. It can be shown that the bulk density–water content relationship for the soil units between cracks is unidimensional when the soil as a whole is in the equidimensional, normal shrinkage phase, and this suggests that these workers preferentially collected samples between cracks. Perroux et al. (1974) also found different shrinkage relationships in the field and for cores in the laboratory.

The field behavior has neither been definitively described nor related to small core measurements. This experiment was designed to bridge the gap between the small core and field studies by using large, undisturbed cores.

MATERIALS AND METHODS

Soil Sampling

Undisturbed cores 73 cm in diam and 150 cm long were collected from the eight Vertisols by the method of Tackett et al. (1965). No compaction was observed at the soil surface. Generally, the cores broke along slickensides that extended obliquely into the cylinder. The resulting holes were filled with gravel, protruding soil was cut away, and a wooden base was attached.

Aluminum access tubes were installed in the center of each core. Stainless steel rods 30 cm long and 0.6 cm in diam were inserted horizontally through slits in the cylinder wall at 15-, 30-, 55-, 95-, and 115-cm depths. The slits were covered with plastic strips.

Experimental Procedure

The cores were placed in a pit under a rainout shelter, and sorghum plants were established in each core in late July 1977. When the plants were at the 12-leaf stage, watering was stopped, and soil shrinkage during the ensuing drying cycle was measured. Nine positions were marked on the soil surface by small, flat plastic strips placed in a cross pattern. The position of these markers, relative to a bar placed across the top of the cylinder, was measured with a meter rule to obtain vertical shrinkage. The position of each side rod relative to the top of the cylinder was measured with a steel tape to obtain the vertical shrinkage within the core below that particular rod. Water loss from the cores was measured with a load cell suspended from a mobile derrick. The load cell was measured to the nearest millivolt, equivalent to 0.45 kg. Weight losses were converted to water use in centimeters using the internal cross section of the cylinder (0.45-kg water use = 0.092 cm water use). No corrections were considered necessary for weight changes in the plants. The shrinkage and weight measurements were made every 2 to 4 days while the plants were actively growing and at longer intervals thereafter.

The plants grew actively for about 25 days in all sites, except site no. 7 (severe wilting was noted after 13 days) and sites no. 2 and 6 (active growth for about 20 days). During October and November, the plants were dead, but measurements were continued at irregular intervals.

Neutron and Density Probe Data Interpretation

The volumetric water content (θ_v) and wet density (the mass of soil and water per unit volume of soil, ρ_w) were obtained with neutron and gamma probes at about 8-day intervals during active plant growth and twice after plant death. With the measured shrinkage within the profile (from the side rods), these data allowed calculation of the shrinkage curve for various depth increments.

The interpretation of the neutron and density probe data is complicated in Vertisols by the bulk density-water content relationship and by cracking near access tubes. In this experiment, a 2- to 3-cm wide crack developed between the core and the cylinder. Small cracks formed around the access tube and in the soil surface. If equidimensional, normal shrinkage is assumed, the soil condition measured by the probes lies between two limiting conditions: (i) all the cracks present were measured (this is the field "soil" condition), and (ii) no cracks occurred within the measured volume (this refers to the "clod" between the cracks). Consequently, the "soil" volume is equal to the "clod" volume plus the volume of cracks. Due to the observed crack pattern, the measured condition was probably closer to the "clod" condition.

Since the volume of the "clod" decreases faster than the volume of the "soil" when water is lost, and volumetric water contents are based on the "soil" volume, water losses calculated from the in situ measurements in the large cores are likely to be underestimated. We used two methods to attempt to overcome these errors.

Method 1—Since the gravimetric water content (θ_g) is independent of the volume considered, the calculated $\theta_g = \theta_v/(\rho_w - \theta_v)$ is correct, provided θ_v and ρ_w are determined on the same volume. Bulk density (B) and vertical shrinkage (Δz) correspond- to this θ_g were obtained from the small core data of Yule and Ritchie (1980) and Θ (cm of water) was calculated for each increment, as $\Theta = \theta_g B(z - \Delta z)$ where z is the fully wet depth of the increment.

Method 2—The density probe gave consistent readings during the experiment, and, therefore, a computation based only on the ρ_w data was developed. The profile was partitioned according to the initial position of the side rods, and the mean ρ_w for these increments was obtained for each measurement date. An equivalent mass of soil (m_s) in each increment was calculated from the bulk density at the swelling limit (small core data of Yule and Ritchie, 1980). Assuming equidimensional shrinkage, we calculated the volume of this core (V_c) on each measurement date from the measured vertical movement of the side rods (Δz). Since $\rho_w = (m_s + m_w)/(V_c)$, the mass of water in the increment (m_w) was obtained. This was converted to Θ cm of water using the initial cross-sectional area since this included the area of any cracks present.

RESULTS AND DISCUSSION

The water loss of representative cores is shown in Fig. 1 as a function of estimated cumulative potential evapotranspiration (Ritchie, 1975). Typically the water loss was proportional to the potential evapotranspiration during the period of active growth (sites no. 3 and 7, Fig. 1). This water loss phase was called the transpiration phase. The average rate of water loss during the transpiration phase was 8.3 mm/day (range 7.6–9.2 mm/day and was higher than the potential evapotranspiration, presumably due to localized advection.

The amounts of water lost during the transpiration phase are listed in Table 1. If these data indicate plant-available water, the general trend is consistent with Yule and Ritchie (1980) except that the water loss seems too high for site no. 1 and too low for site no. 7.

The transpiration phase was followed by another approximately linear phase with considerably decreased slope (sites no. 3 and 7, Fig. 1). This decrease was not due to a decrease in the potential evaportanspiration rate. This phase was called the soil evapora-

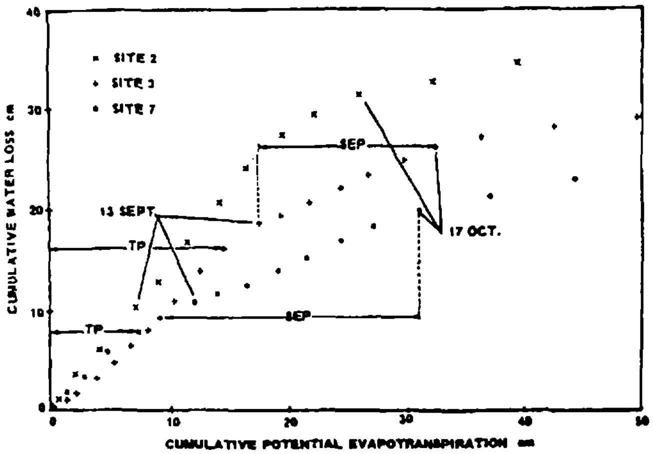

Fig. 1—The water loss as a function of potential evapotranspiration. The last data point was collected on 27 November. The water loss phases are indicated for sites no. 3 and 7. *TP* = transpiration phase; *SEP* = soil evaporation phase.

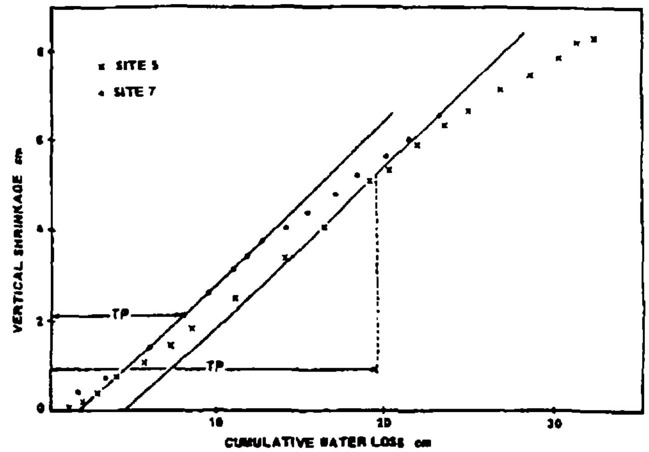

Fig. 2—The relationship between the vertical shrinkage of the core surface and the cumulative water loss. The transpiration phase (*TP*) is marked. The equidimensional, normal curve is drawn through the point at the end of the transpiration phase for each site.

tion phase because water loss was apparently dominated by evaporation from the side of the core. The average rate of water loss was 3.8 mm/day (range 3.2-4.8 mm/day). This rate is high for evaporation from dry soil, but the crack between the core and the cylinder exposed up to seven times more soil surface. Probably an annulus of the core only 5 or 6 cm wide was affected, but such an annulus would contain about 25% of the core. Due to position, no measurements except the core weight would be expected to respond to such water loss. The duration of the soil evaporation phase was at least 25 days (Fig. 1).

The contribution of the soil evaporation phase during the transpiration phase is uncertain. The crack between the core and the cylinder was developing; plant transpiration dissipated most of the incoming energy; and the plants provided considerable shade. After midOctober, the sides of the cores were sufficiently dry to limit evaporation, and the water loss rates decreased (Fig. 1).

Water loss at sites no. 2 and 6 was atypical due to slow plant establishment and did not have the same two-phase pattern (Fig. 1, site no. 2). Apparently, plant-water use and soil evaporation were occurring simultaneously at these sites.

Vertical Shrinkage

The mean vertical shrinkage for the nine surface plates was calculated. The C.V. was < 10% during most of the experiment and at the conclusion averaged 3.7% over all sites (range 2.1–6.0%). This amount of variability was comparable to that for the 10-cm cores (Yule and Ritchie, 1980). The large cores were apparently uniform even at the gilgai sites where differences in soil properties were considerable within 4 m (Yule and Ritchie, 1980). Vertical shrinkage measured near the core center and toward the side of the core were similar. The shrinkage measurements apparently did not reflect water losses from the side of the core.

Table 1—Water loss during the transpiration phase.

Site	Water loss, cm
1	20.0
3	18.5
4	16.5
5	19.0
7	8.5
8	15.3

Typical vertical shrinkage curves are shown in Fig. 2. The data approached asymptotically the theoretical curve in the transpiration phase and deviated increasingly in the soil evaporation phase. During the transpiration phase, the structural water loss decreased and the shrinkage water loss dominated as the theoretical curve was approached. The deviation during the soil evaporation phase occurred because the shrinkage measurement did not respond to water loss from the side of the core.

The trends in water loss with profile depth are indicated in Fig. 3, which shows that the onset of vertical shrinkage (and water use in the shrinkage phase) occurred after greater cumulative water loss with increasing profile lepth. This trend was very consistent for all sites. Very little shrinkage water was used be-

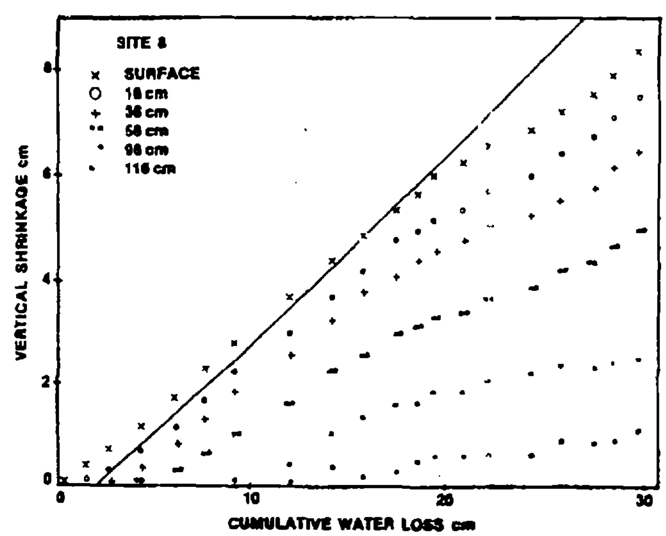

Fig. 3—The relationship between vertical shrinkage at several depths within the core and the cumulative water loss. The theoretical curve is drawn as in Fig. 2.

Table 2—Large core water loss parameters during the transpiration phase.

Site	Structural water loss	Shrinkage water loss	Vertical shrinkage
		cm	
3	3.4	16.1	5.3
4	4.3	12.2	4.2
5	5.1	13.9	5.0
7	1.8	6.7	2.3
8	2.2	13.1	4.6

low 115 cm (core depth was 134 cm) before the plants were in severe stress. The plots for each depth were reasonably parallel, which indicates that most of the water in a zone was extracted before shrinkage water was used from deeper zones.

Sites no. 2 and 6 did not show the strong asymptotic trend toward the theoretical curve shown in Fig. 2 and 3. This is consistent with the previous observation that soil evaporation contributed simultaneously with plant uptake at these sites.

Due to the problems described, it was difficult to accurately partition the water loss into structural and shrinkage phases. However, this was attempted for some sites (Table 2). These results were generally consistent with the small core data except for small values for site no. 7.

Neutron and Density Probe Results

Measured and calculated water loss and vertical shrinkage for method 1 are compared in Table 3. All sites, except no. 7, showed similar comparisons. Reasonable agreement was found, but trends with time were not always consistent, and large differences occurred over short time periods. No consistent effect of water loss mechanism was evident.

Shrinkage curves for representative depth increments are shown in Fig. 4. Although there was some scatter, the plots were generally similar to equivalent plots of Yule and Ritchie (1980). The volumetric water content at the swelling limit was calculated. These values agreed reasonably well with the equivalent data from small cores (Table 4).

The water losses calculated by *Method 2* are com-

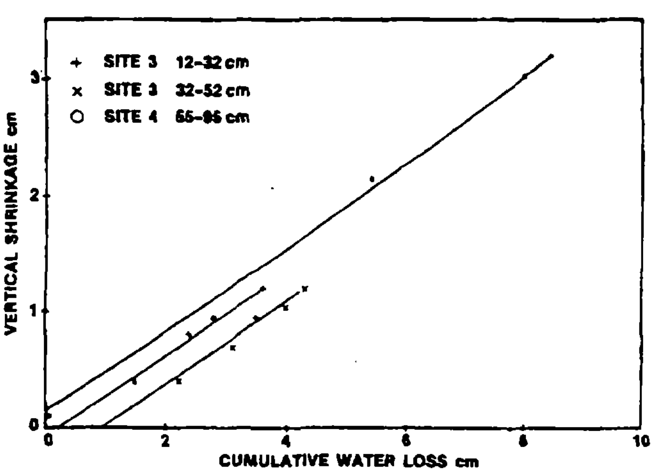

Fig. 4—Vertical shrinkage as a function of water loss (from neutron data, Method 1) for three depths increments of the large cores. The equidimensional, normal curve is plotted for each increment.

Table 3—Comparison between the calculated total water loss and total vertical shrinkage (by Method 1) and the corresponding measured values at various times. All data are referenced to 26 August.

Site	Date	Water loss Calculated	Water loss Measured	Vertical shrinkage Calculated	Vertical shrinkage Measured
			cm		
1	3 Sept.	4.5	7.7	1.4	1.6
	20 Sept.	18.3	17.3	5.2	4.1
	14 Oct.	24.7	24.7	7.1	5.5
	27 Nov.	25.2	27.7	7.1	6.4
3	3 Sept.	10.9	9.2	2.3	2.9
	20 Sept.	18.3	16.0	4.7	5.2
	14 Oct.	24.1	22.1	6.5	7.0
	27 Nov.	26.1	24.2	7.0	7.7
4	3 Sept.	5.0	7.6	2.1	2.1
	20 Sept.	12.8	14.8	4.3	4.2
	14 Oct.	24.0	23.9	7.9	6.4
	27 Nov.	23.3	27.3	8.0	7.1

pared to measured values in Table 5. The results are better than those obtained with *Method 1*, except for site no. 3, where only the differences are consistent. The calculated amount of water in the profile was very sensitive to the values used for the initial bulk density profile, which defined the mass of soil. Consequently, the calculated water content profiles were not consistent, and values obtained for the swelling limit did not compare well with the small core data. However, the general shape of the shrinkage curve resembled that in Fig. 4.

In summary, the neutron and density probes gave a reasonable indication of the profile distribution of water content, and these methods of calculation over-

Table 4—The volumetric water content at the swelling limit calculated from large core and small core data for similar depth increments.

Depth†	Site 1 Small core	Site 1 Large core	Site 3 Small core	Site 3 Large core	Site 4 Small core	Site 4 Large core
1	0.41	0.43	0.44	0.43	0.40	0.39
2	0.39	0.35	0.42	0.41	0.43	0.41
3	0.32	0.29			0.44	0.46

† Depth 1 is 10–20 cm for small cores, 15–35 cm for large cores; depth 2 is 40–50 cm for small cores, 35–55 cm for large cores; and depth 3 is 70–80 cm for small cores, 65–95 cm for large cores.

Table 5—Comparison between the calculated total water loss (by Method 2) and the measured values at various times. Data are referenced to the start of the drying cycle (26 Aug. for sites no. 3 and 4; 3 Sept. for site no. 6).

Site	Date	Water loss Calculated	Water loss Measured
		cm	
3	3 Sept.	13.5	9.2
	20 Sept.	21.4	16.0
	14 Oct.	26.8	22.0
	27 Nov.	29.2	24.2
4	5 Sept.	8.2	7.6
	20 Sept.	17.5	14.8
	14 Oct.	25.1	23.9
	27 Nov.	26.2	27.3
6	20 Sept.	13.7	12.4
	14 Oct.	23.8	26.1
	27 Nov.	28.4	30.1

came, at least in part, the problems associated with soil shrinkage around the access tube. The data were not sufficiently precise to allow determination of the amount of structural water loss in various soil increments or to examine the effects of overburden (present in the large cores but not in the small cores) on the shrinkage curve.

CONCLUSIONS

The evidence suggested that the large cores exhibited very similar shrinkage behavior to the small cores. Therefore, if the large cores are indeed representative of field behavior, the small core data can be used to predict field responses if the soil water contents in the field are known.

Interpretation of field-surface, vertical shrinkage measurements will be complicated by simultaneous structural and shrinkage water loss occurring at different depths in the profile. Although eventually the whole profile will reach the shrinkage water-loss phase, this may not occur until most of the plant-available water has been used. Consequently, empirical relationships may be needed to predict water losses from surface-shrinkage measurements.

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Deficit, High-frequency Irrigation of Sugarbeets with the Line Source Technique[1]

D. E. Miller and An N. Hang[2]

ABSTRACT

Studies were conducted on sandy and loam soils to determine the effect of deficit, daily sprinkler irrigation on sugar production from sugarbeets (*Beta vulgaris* L.) using the line source technique. With a loam soil near the upper limit of available water at the start of the irrigation season, daily sprinkler irrigation rates of sugarbeets were reduced to 35 to 50% of estimated evapotranspiration (ET) rates without reducing sugar yields. On a sandy soil, sugar yields increased with irrigation rates up to 100% estimated ET, the maximum rate applied.

Additional Index Words: **evapotranspiration, sugar percentage, sprinkler irrigation, available water, soil water depletion.**

Miller, D. E., and A. N. Hang. 1980. Deficit, high-frequency irrigation of sugarbeets with the line source technique. Soil Sci. Soc. Am. J. 44:1295–1298.

Many irrigation studies have involved intermittent irrigation with depletion of soil water to different degrees between irrigations. Under such conditions, Jensen and Erie (1971) concluded that sugarbeets (*Beta vulgaris* L.) could be grown satisfactorily either at high soil water levels, maintained by light, frequent irrigations, or that 60 to 70% of the available water could be depleted between irrigations. Kohl and Cary (1969) found that the degree of water stress indicated by afternoon wilting of sugarbeets did not affect root yields. Ehlig and LeMert (1979) systematically overirrigated or underirrigated sugarbeets so that the seasonal application ranged from 11% above to 23% below that needed to replace evapotranspiration (ET), as measured with a lysimeter. Neither sugar content nor yield was affected by the irrigation treatments.

Fonken et al. (1974), using solid-set sprinklers, noted that their irrigation intervals did not affect sugar yields in Nebraska. In that area, where summer rainfall provides a substantial part of the water used by plants, they found that water applications could be about one third less than peak ET rates without reducing sugar yields. They emphasized the need to start the irrigation season with a full or nearly full soil water profile. Aarstad and Miller (1973) obtained

[1] Contribution from Science and Education Administration, USDA-AR, in cooperation with the College of Agriculture Research Center, Washington State University, Pullman, Scientific Paper no. 5599 of the latter. Received 28 Apr. 1980. Approved 4 Aug. 1980.

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Root Growth in a Claypan with a Perennial-Annual Rotation

S. J. Grecu, M. B. Kirkham,* E. T. Kanemasu, D. W. Sweeney, L. R. Stone, and G. A. Milliken

ABSTRACT

Drought stress occurs on claypan soils because they restrict root growth and water uptake. This research sought to determine if alfalfa (*Medicago sativa* L.) planted with fescue (*Festuca arundinacea* Schreb.) would decrease penetration resistance of a claypan soil enough to justify a regular rotation of the legume-grass mixture with annual summer crops of maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. The study was carried out in southeast Kansas on a Parsons silt loam (Mollic Albaqualf; fine, mixed, thermic), overlying clay (the claypan). Alfalfa + fescue were grown for 2 yr and disked. Maize or soybean then was planted on these plots. Control plots contained either maize or soybean for 3 yr. After 3 yr, penetration resistance, bulk density, soil-water content, and root length density were measured. Growing alfalfa + fescue had no effect on the penetration resistance or bulk density of the soil. At the beginning of the third year, plots previously planted with alfalfa + fescue had less water in the claypan than continuous plots of maize or soybean. Maize grown on continuous plots had more roots, was 0.3 m taller at tasseling, and had a greater yield (although still low due to the dry summer) than maize grown on plots previously planted with alfalfa + fescue. This increased growth was due partly to the greater amount of water available in the continuous plots. Roots of both maize and soybean penetrated the claypan to the maximum depth of observation (1.35 m from the soil surface). Root length densities in the claypan were greater for maize than for soybean.

Additional Index Words: Medicago sativa L., *Festuca arundinacea* Schreb., *Zea mays* L., *Glycine max* (L.) Merr., Alfalfa, Fescue, Maize, Soybean, Penetration resistance, Soil-water content, Root length density.

The ability of deep-rooted perennial legumes to penetrate pans is well documented (Bowen, 1981). Alfalfa, in particular, has great value as a soil-improving crop, especially if a perennial grass is planted with it. Alfalfa and grass can exploit the total soil environment more effectively than either one alone. Grass roots tend to concentrate in the upper part of the soil, whereas the alfalfa roots proliferate at greater depths (Chamblee, 1972). Larson and Allmaras (1971) state that rotation of annual crops with perennial grasses and legumes alleviates soil compaction.

Alfalfa depletes the subsoil of water. Experiments done near Manhattan, KS, in the 1920s and 1930s showed that alfalfa used subsoil moisture to a depth of 7.6 m within 2 yr after seeding, and plots had to be fallowed 2 to 4 yr or longer to restore the deep subsoil moisture (Duley, 1929; Duley and Metzger, 1932–1934; Grandfield, 1934–1936; Grandfield and Metzger, 1936). More recently, in Australia, Smith (1977) reported that yields of wheat (*Triticum aestivum* L.) were increased when it was grown after alfalfa, but only if moisture was not limiting. The results also indicated that alfalfa was inappropriate in a rotation under low moisture conditions. Despite this depletion of subsoil moisture, annual crops are still grown after alfalfa, because it is believed that deep-rooted alfalfa should not interfere with the satisfactory production of more shallow-rooted annual crops (Grandfield and Throckmorton, 1945).

Our study focused on both the soil-improving ability of alfalfa and its water-extraction pattern. A claypan, extending from 0.25 m to bedrock, underlies the topsoil in southeastern Kansas. Even though this part of the state receives an average yearly rainfall of 0.93 m (Kansas State Board of Agric., 1985), drought stress is a chronic problem, because the claypan restricts root growth and water uptake. Maize and soybean are two of the most important annual summer crops grown in the area. The objective of this research was to determine if alfalfa planted with a grass (fescue) could decrease penetration resistance of the soil to a degree that justified a regular rotation of this mixture with the annual summer crops. In addition, to measure how much subsoil moisture the alfalfa and fescue mixture depleted, we quantified the water content in fields with maize or soybean, which had previously been planted with alfalfa and fescue, and compared it with the water content in fields with continuous maize or continuous soybean. Finally, we wanted to determine if roots of maize and soybean penetrated the claypan.

MATERIALS AND METHODS

The experiment was conducted for 3 yr (1982 through 1984) at the Southeast Kansas Exp. Stn., Parsons, KS. The topsoil at the station is a Parsons silt loam. The soil profile has the silt-loam (Ae) horizon, 0.25 m in depth, which overlies an argillic (clay) Bt horizon extending to 2.0 m, where it is bound by a C horizon of soft sandstone. The clay horizon is classified as a claypan (SSSA, 1987). Figure 1 shows the water content at different soil-water potentials for the silt loam and the clay.

In 1982, 32 experimental plots, each measuring 6 m by 6 m, were established. The experiment was a randomized complete block with eight treatments and four replications. Figure 2 shows the plots. The area was level, and run-off and run-on were not significant. On 31 Mar. 1982, before planting, 16 plots were chiseled at a depth of 0.60 m with three chisels 0.45 m apart. The other 16 plots were not chiseled. Plots were not deeply chiseled in 1983 or 1984. In 1982 and 1983, one-half of the plots were planted with a mixture of alfalfa ('Classic') and fescue ('Kentucky 31'), one-quarter were planted with maize ('NC+59'), and one-quarter were planted with soybean ('Essex'). On 29 Nov. 1983, the plots with alfalfa and fescue were shallowly chiseled to a depth of 0.15 to 0.20 m to destroy the legume-grass stand. On 1 May 1984 all 32 plots were shallowly chiseled and disked. On 9 May 1984 maize ('NC+90') was planted on plots that had been in maize for two seasons and in half of the plots that had been in alfalfa + fescue for two seasons. On 15 June 1984, soybean (Essex) was planted in plots that had been in soybean for two seasons and in the other half of the plots that had been in alfalfa + fescue for two seasons. Before planting, maize was fertilized with 134, 20, and 37 kg/ha of

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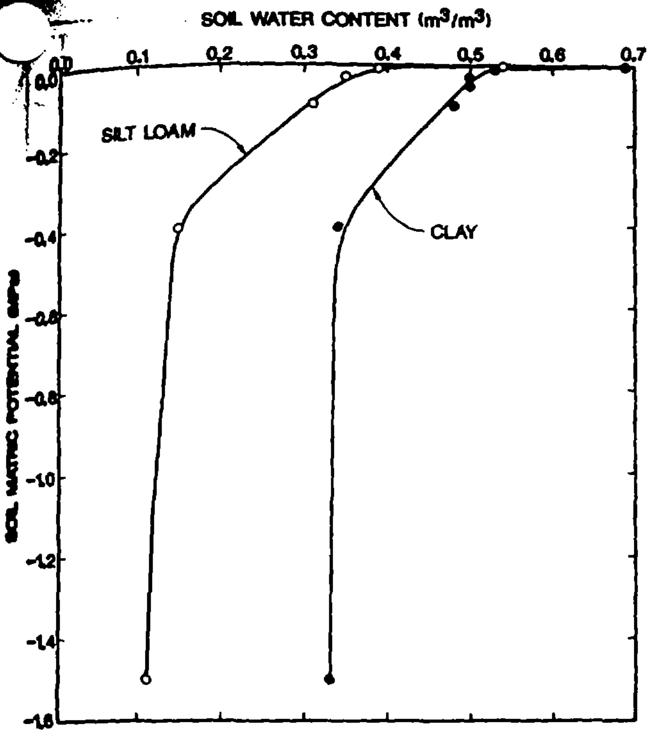

Fig. 1. Water content of the experimental soil at different matric potentials.

N, P, and K, respectively, and soybean was fertilized with ' and 18 kg/ha of P and K, respectively.

Table 1 shows temperature and rainfall during the years of the experiment (1982, 1983, 1984). The summer of 1982 had relatively normal temperatures and precipitation. The summer of 1983 was hot and dry. The summer of 1984 was dry with relatively normal temperatures (Natl. Oceanic and Atmosph. Admin., 1982, 1982–1984).

In 1984 penetration resistance, soil-water content, and number of roots were measured between 8 June (calendar Day 160) and 10 Aug. (Day 223) for maize and between 13 July (Day 195) and 21 Sept. (Day 265) for soybean. Penetration-resistance measurements of the soil were made with a hand-held penetrometer (Soiltest, Inc., Evanston, IL). The penetrometer had a 60° included angle cone tip (base diameter of 0.0063 m) and was forced manually into the soil to the 0.150- and 0.450-m depths. Three samples per plot were taken on each measurement day by the same person

Table 1. Monthly averages of rain and temperature during the experiment.†

Month	1982 Rain	1982 Temp.	1983 Rain	1983 Temp.	1984 Rain	1984 Temp.	30-yr avg. Rain	30-yr avg. Temp.
	mm	°C	mm	°C	mm	°C	mm	°C
Jan.	64	−3.1	27	0.8	12	−3.0	31	0.4
Feb.	–‡	0.1	42	3.3	62	4.7	34	3.6
Mar.	79	8.7	122	6.9	147	5.4	76	8.4
Apr.	43	12.2	200	9.2	156	11.7	95	15.0
May	208	19.3	125	16.4	105	17.3	132	19.8
June	165	20.9	130	22.2	74	24.6	122	24.5
July	87	27.1	18	26.7	27	25.8	93	27.4
Aug.	96	26.6	39	28.6	18	26.3	87	26.6
Sept.	38	21.4	57	20.8	46	20.1	115	22.3
Oct.	45	14.1	224	14.5	243	14.2	88	16.3
Nov.	85	7.3	76	8.5	54	6.8	65	8.6
Dec.	104	4.1	21	−6.9	80	4.4	42	3.1

† Data from Nat. Oceanic and Atmos. Admin. (1982; 1982–1984). The weather station was 160-m south of the experimental plots.
‡ Missing data.

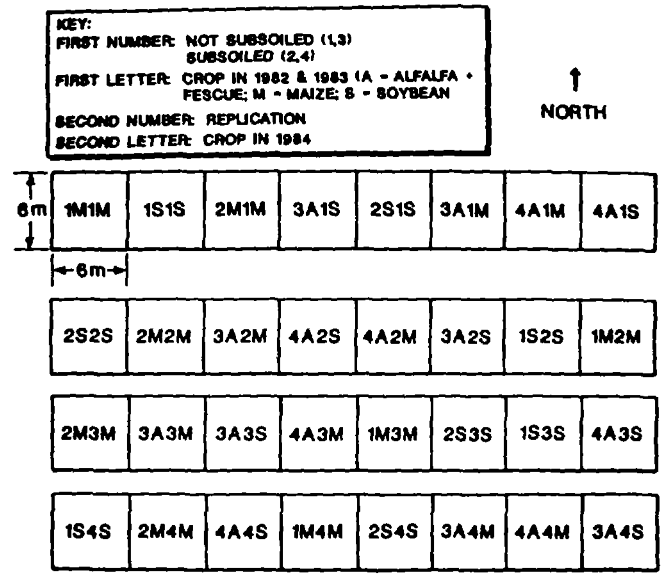

Fig. 2. Layout of the experimental plots.

to ensure consistency. Penetrometer measurements were obtained as follows. A core 0.025 m in diameter was taken with a Giddings probe (Giddings Machine Co., Fort Collins, CO), to the 0.150-m depth, to eliminate friction unrelated to penetration resistance, before forcing the penetrometer into the soil. After the 0.150-m depth measurement was made, an additional core, 0.025 m in diameter, taken with the Giddings probe, was removed from the 0.150- to 0.450-m depth. The penetration resistance of the soil at the 0.450-m depth was then determined.

Soil-water content was determined, from a depth of 0.150 to 1.35 m in 0.150-m increments, by using a neutron attenuation probe (Model 3221, Troxler Electronic Lab., Inc., Research Triangle Park, NC). The aluminum neutron-access tubes were installed vertically with the Giddings probe, one tube per plot. Penetration-resistance and soil-water measurements were taken at the same time.

Roots were counted with minirhizotrons, which are transparent, plastic tubes inserted into the ground. They are used to make nondestructive, economical, and rapid measurements of root growth and distribution (Meyer and Barrs, 1985; Sanders and Brown, 1978; Upchurch and Ritchie, 1983). In our study, each minirhizotron was an extruded acrylic tube (Cadillac Plastic and Chemical Co., Lexena, KS), 1.8 m in length, with an o.d. of 0.076 m and an i.d. of 0.070 m. Tubes were inserted into the soil at a 30° angle to the vertical to minimize roots growing along the plastic tubes (Bragg et al., 1983). The top 0.25 m of the minirhizotron was aboveground and was protected between measurements from debris and light with a capped sewer pipe. The bottom of the minirhizotron was sealed with a rubber stopper. The figures in this paper show the depth of roots vertically from the soil surface. Each plot had three minirhizotrons inserted in the same plant row containing the neutron attenuation probe. The Giddings probe was used to install the minirhizotrons. The surface of each minirhizotron was etched in a 0.050- by 0.050-m grid and then marked at different depths. Roots were observed in each minirhizotron by using a top-reflecting mirror illuminated with one 15-W light bulb, which was attached to a long rod and a dry-cell battery. The number of roots crossing each 0.050- by 0.050-m grid in each tube was counted.

Root length density was determined by using the equation of Melhuish and Lang (1969)

$$L_T = 2n$$

where n = mean number of roots per unit area (no./m^2)

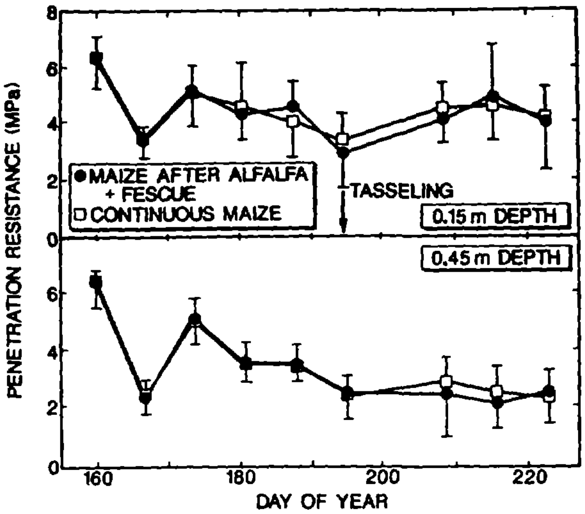

Fig. 3. Penetration resistance at two depths in plots with continuous maize for three seasons or with alfalfa + fescue for 2 yr followed by maize for one season. Vertical bars show half the standard deviation.

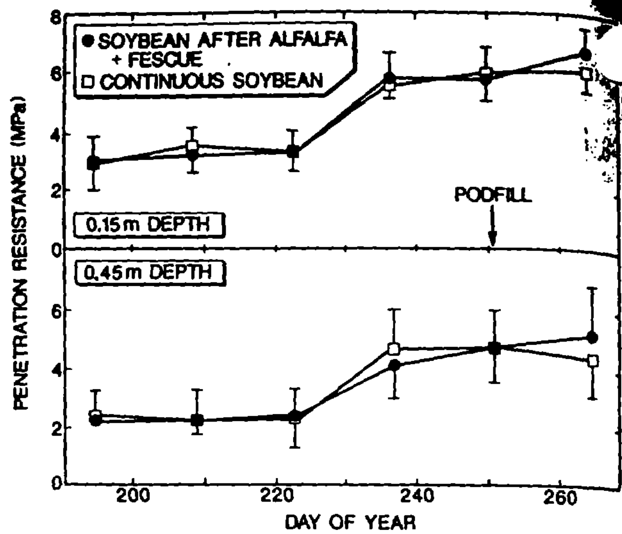

Fig. 4. Penetration resistance at two depths in plots with continuous soybean for three seasons or with alfalfa + fescue for 2 yr followed by soybean for one season. Vertical bars show half the standard deviation.

and L_T = total probable mean length per unit volume (m/m^3). Since the area of each grid was 0.0025 m^2 (0.050 by 0.050 m), root number was multiplied by 800 (2/0.0025) to obtain the root length density (m/m^3).

On 13 July 1984 height of the maize was measured. Height of soybean was not measured. On 20 July 1984 bulk densities were determined by taking one core per plot (67-mm diam) to a depth of 1.05 m and slicing it at 150-mm intervals. The samples were oven-dried for 48 h at 105 °C and weighed. On 29 Sept. 1984 maize and soybean were harvested. Three rows per plot (0.76 m in each row) were taken for yield data.

Results from the plots that were subsoiled and plots that were not subsoiled were averaged together, because the subsoiling in March 1982 did not have significant effects on the measurements taken in 1984. The lack of effect of subsoiling agrees with previous results obtained at the Southeast Kansas Exp. Stn. Breaking up the claypan by using mechanical tillage has been unsuccessful because, after wetting, the soil returns to its original condition (R.J. Johnson, 1982, personal communication). Lumping subsoiled and nonsubsoiled plots resulted in eight replications per rotation. Least significant differences (LSD, 0.05 level) were calculated for the data.

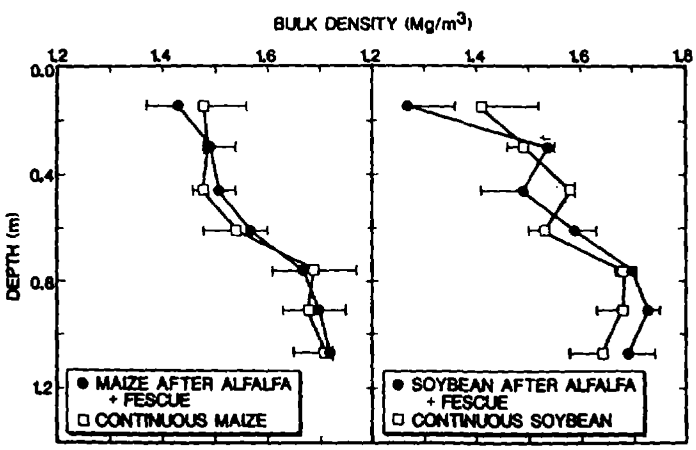

Fig. 5. Bulk density at different depths. Left: Plots with continuous maize for three seasons or with alfalfa + fescue for 2 yr followed by maize for one season. Right: Plots with continuous soybean for three seasons or with alfalfa + fescue for 2 yr followed by soybean for one season. Vertical bars show half the standard deviation.

RESULTS AND DISCUSSION

Penetration Resistance and Bulk Density

Both in the topsoil and claypan (0.15- and 0.45-m depths), penetration resistance in plots that had continuous crops was similar to that in plots previously containing alfalfa + fescue (Fig. 3, 4). Therefore, the alfalfa + fescue treatment had no measurable effect on decreasing the strength of the pan. Penetration resistance was generally higher in the topsoil than in the claypan, probably because the topsoil was usually drier, although variation in soil texture between the topsoil and claypan also could have caused differences (Vepraskas, 1984). Bulk density in plots that had continuous crops was similar to that in plots which previously had alfalfa + fescue (Fig. 5). Thus, neither penetration resistance nor bulk density was affected by the grass-legume mixture.

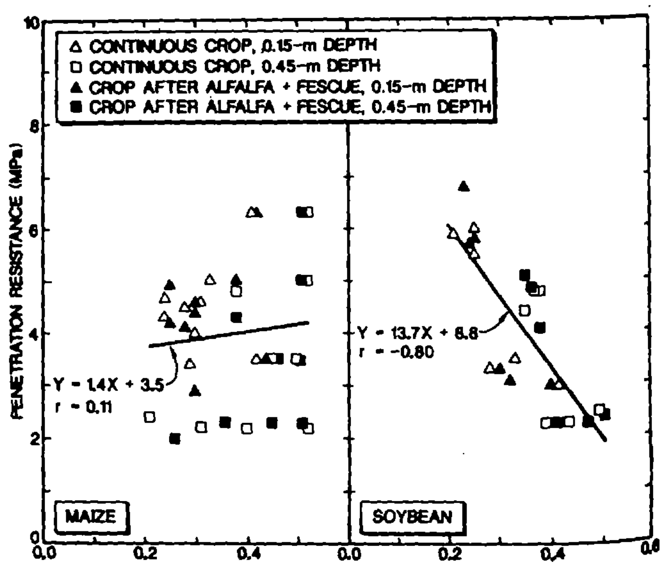

Fig. 6. Penetration resistance vs. soil-water content.

Soil-water Content

Penetration Resistance

There was an inverse correlation between penetration resistance and soil-water content for soybean but not for maize (Fig. 6). For maize, penetration resistance and soil-water content were not correlated. This was probably due to rainfall. Measurements of penetration resistance and soil-water content began for maize on Day 160 (8 June), but they did not begin until Day 195 (13 July) for soybean. From Day 160 through 195, 96 mm of rain fell. Between the time that measurements of soybean began and measurements of maize ceased (Day 195 through Day 223 or 10 August), 11 mm of rain fell. During the rest of the season, until measurements of soybeans ceased (Day 223 through Day 265 or 21 September), 49 mm of rain fell. Soybean received less water during the season. The results suggested that the relation between penetration resistance and soil-water content was stronger when there was less rainfall than when there was more rainfall.

Maize

On the first day of measurement (8 June 1984), there was more water in the soil above 0.45 m and less water below 0.45 m in the plots that had previously had alfalfa + fescue than in plots that had previously had only maize (Fig. 7). On the last day of measurement

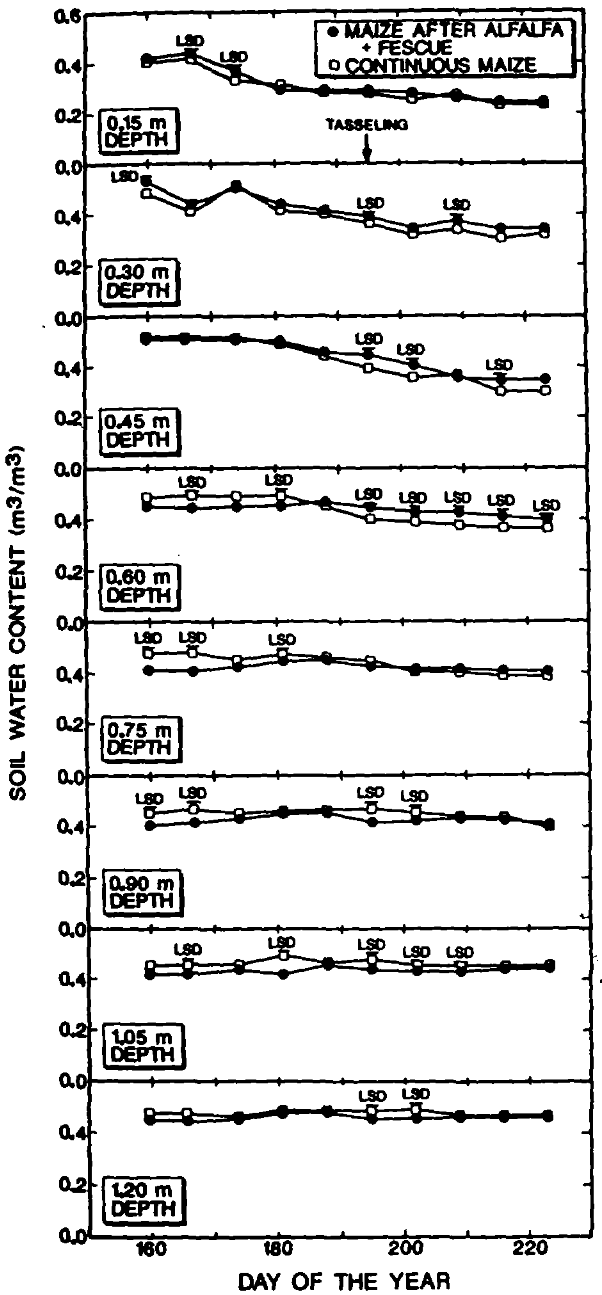

Fig. 7. Soil-water content at different depths in plots with continuous maize for three seasons or with alfalfa + fescue for 2 yr followed by maize for one season. The LSDs are shown only for dates on which significant differences occurred.

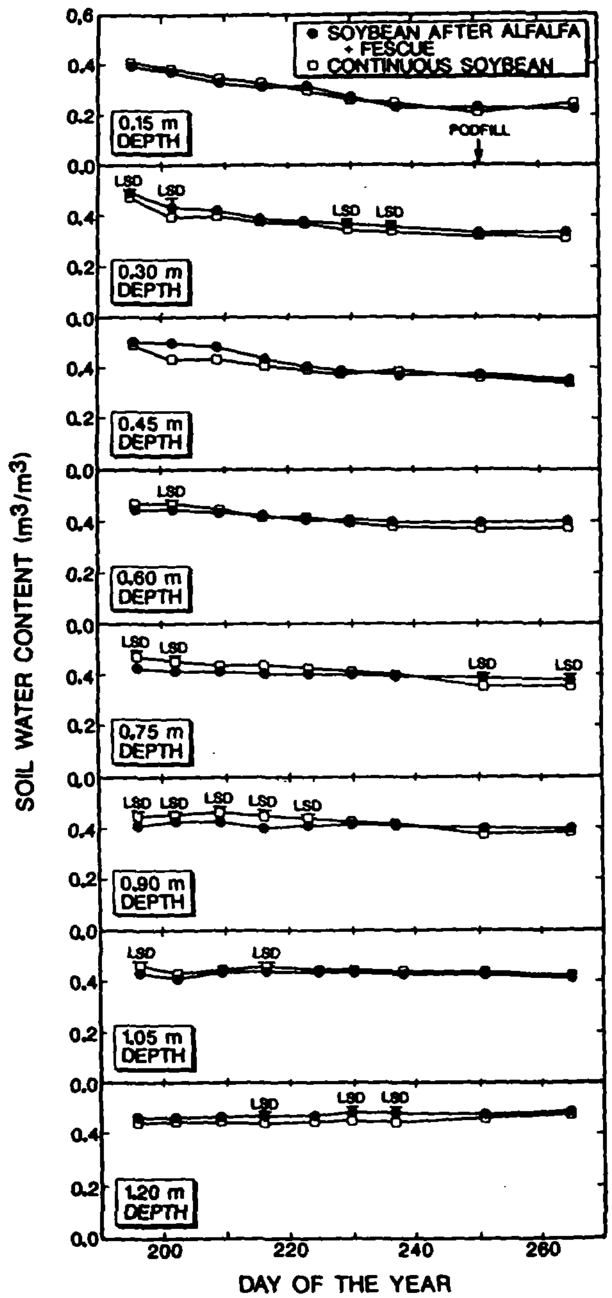

Fig. 8. Soil-water content at different depths in plots with continuous soybean for three seasons or with alfalfa + fescue for 2 yr followed by soybean for one season. For LSD, see legend to Fig. 7.

(10 Aug. 1984), the upper part of the soil (above 0.75 m) that previously had alfalfa + fescue was wetter than the upper part of the soil with continuous maize. The wetter soil at shallow depths suggested that the alfalfa + fescue previously planted in the plots had not extracted as much water from the topsoil as had continuous maize. This agrees with data of Saini and Chow (1982), who grew maize or alfalfa in wooden boxes 0.75 m deep. At the 0.15-m depth, soil was drier with maize than with alfalfa, but at the 0.60-m depth, the soil was drier with the deep-rooted alfalfa than with shallow-rooted maize.

Soybean

As with maize, initially (13 July 1984) there was more water in the soil above 0.45 m and less water below 0.45 m in the plots that had previously had alfalfa + fescue than in plots that had previously had only soybean (Fig. 8). At the end of the season (21 Sept. 1984), the upper part of the soil (above 0.90 m) that previously had alfalfa + fescue was wetter, except for the top (0.15 m) measurement, than the upper part of the soil with continuous soybean. The difference between the 0.90- and 0.75-m depths for the wetter part of the soil for soybean and maize, respectively, might have been due to the different rooting patterns. Maize had a greater root length density at all depths compared to soybean (see next section).

Roots

Maize

Roots of maize grew into the claypan. After Day 174, continuous maize had more roots at all depths down to 1.05 m than maize following alfalfa + fescue, but significant differences occurred only at the depths shown in Fig. 9 (note LSD values). Roots extended to the bottom of the minirhizotron (1.35 m below the soil surface), but below 1.05 m there were no significant differences in root numbers between treatments. The greater number of roots of continuous maize at depths below 0.60 m, extending down to 0.90 m, agreed with the greater water depletion (lower soil-water content) at these depths by continuous maize compared with maize that followed alfalfa + fescue (Fig. 7). At 0.90 m and below, continuous maize also had more roots than maize planted after alfalfa + fescue (Fig. 9). But the soil with continuous maize had a higher water content than soil with alfalfa + fescue followed by maize (Fig. 7). Apparently, the roots of continuous maize at these low depths were not extracting water. Major water uptake appeared to be between 0.30 and 0.60 m, where differences between the water content of continuous maize and maize followed by alfalfa + fescue were greatest.

Root length density in the topsoil and claypan were low. van Noordwijk and de Willigen (1979) assumed that the root length density for plants, in general, varied from 2000 to 50 000 m/m^3. We measured root length densities <2000 m/m^3 for maize (Fig. 9). Brown and Scott (1984) reported root length densities for maize that varied from about 1000 to 40 000 m/m^3. Root length density in our study was low for at least two reasons. First, the claypan probably inhibited root proliferation. Second, the summer of 1984 was dry. Also, root length density reported in the literature depends upon methodology and different equations used to calculate it (Melhuish and Lang, 1969; Upchurch and Ritchie, 1983).

Soybean

Roots of soybean also grew into the claypan, extending to the bottom of the minirhizotron. Root length densities for soybean were low at all depths and during the entire season (<1600 m/m^3) (data not shown). At no time did root length density of continuous soybean differ significantly from that of soybean grown after alfalfa + fescue. Root length density tended to be maximum at about podfill (Fig. 10).

Arya et al. (1975) found that root length densities of soybean varied from 700 to 50 000 m/m^3. Brown and his colleagues measured extensively the root length density of soybean and found variations from 5 000 to 89 000 m/m^3 (Brown and Scott, 1984; Brown et al., 1985; Sanders and Brown, 1978, 1979). Root length densities in our study fell below this range. The results showed that in a dry year at Parsons, KS, root length density of soybean was less than that of maize. Soybean was planted later than maize and started the season with less total soil profile water (647 mm for alfalfa + fescue treatment and 666 mm for continuous soybean) than did maize (660 mm for alfalfa + fescue treatment and 690 mm for continuous maize). This probably contributed to the poorer root growth of soybean compared to maize.

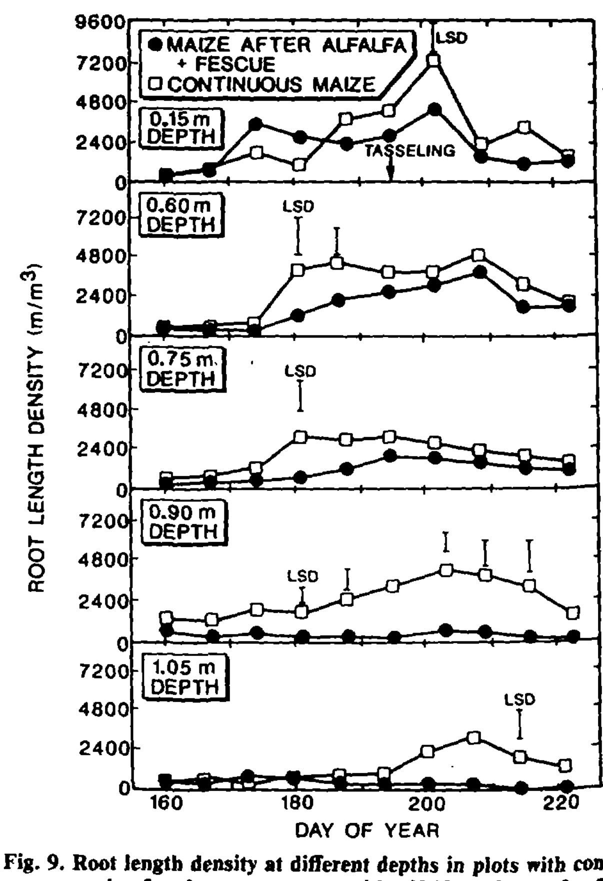

Fig. 9. Root length density at different depths in plots with continuous maize for three seasons or with alfalfa + fescue for 2 yr followed by maize for one season. For LSD, see legend to Fig. 7.

Growth

Yields in 1984 were low because of the below-normal amounts of rain. Maize following alfalfa + fescue and continuous maize yielded 0.63 and 1.47 Mg/ha, respectively (significantly different at the 0.05 level). Maize in 1984 following two seasons of alfalfa + fescue was 0.30 m shorter in height at tasseling than continuous maize. Yields of soybean following alfalfa + fescue (0.17 Mg/ha) and continuous soybean (0.20 Mg/ha) were not significantly different.

CONCLUSION

Alfalfa and fescue, grown for 2 yr (1982 and 1983) on a soil with a 1.75-m claypan overlaid by a 0.25-m silt-loam topsoil, had no effect on the penetration resistance or bulk density of the soil in the third year (1984) when maize and soybean were grown. At the beginning of 1984 soil previously planted with alfalfa + fescue had more water in the topsoil and less water in the claypan than soil planted continuously with maize or soybean. This suggested that deep roots of the alfalfa + fescue mixture had depleted soil moisture at lower depths. Plots with continuous maize had significantly more roots, taller plants, and yielded more grain than did maize following alfalfa + fescue. Plots with continuous soybean also yielded more grain than did plots with soybean following alfalfa + fescue, but the difference was not significant. The greater growth of the continuously planted annual crops appeared to be due, in part, to the greater amount of moisture available in plots with continuous maize or continuous soybean compared to plots previously planted with alfalfa + fescue. The results were similar to those obtained since the 1920s, which show that alfalfa depletes subsoil moisture and, in a dry environment, should not be included in a rotation with annual crops.

Roots of both maize and soybean grew into the claypan and penetrated to the maximum depth of observation (1.35 m from the soil surface). Root length densities of maize were greater in the claypan than those of soybean, suggesting that maize might be better adapted to the claypan.

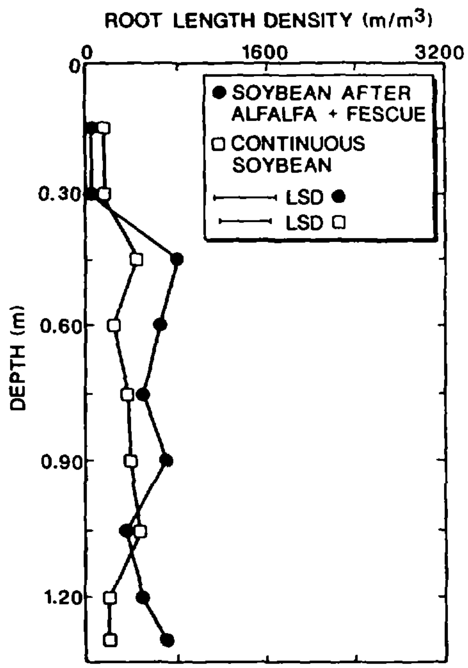

Fig. 10. Root length density in 1984 at different depths in plots with continuous soybean for three seasons or with alfalfa + fescue for 2 yr followed by soybean for one season. Measurements were taken at podfill.

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Optimal Design of Field Experiments for Determination of Production Functions

J. M. H. Hendrickx, P. J. Wierenga,* and N. S. Urquhart

ABSTRACT

A technique was needed to assess the optimal number and size of experimental plots for detection of the shape of a production function with confidence intervals of specified length. Therefore, an equation was developed to evaluate the optimal number of replications and the optimal plot size for field experiments with structured quantitative treatments. Use of the equation is illustrated with experimental designs for determination of water production functions of trickle irrigated chile peppers (*Capsicum annuum* L., var. New Mexico no. 6–4). Input variables for the equation are the variance, error degrees of freedom, plot size of a previous experiment, dependency between adjacent experimental plots of a previous experiment expressed in a coefficient *b*, size of the difference to be detected, assurance with which it is desired to detect the difference, and level of significance to be used in a future experiment. Application of the equation showed that, for detection of small differences, optimization of the plot size becomes important. In our sample experiment we found that a fourfold increase in experimental plot size decreased the total number of plots from 156 to 42, but increased the total experimental area by only 8%.

Additional Index Words: **Trickle irrigation, Water use, Contrast analysis, Chile peppers, Experimental design.**

Production functions usually are based on data obtained from controlled field plot experiments. In these experiments, plot size depends on many factors, including availability of land, labor, type of farm machinery, irrigation system used, and costs. Statistical considerations are equally important in determining plot size. Techniques to determine the optimal number and size of experimental plots were presented by Kempthorne (1952), Federer (1955), Cochran and Cox (1957), Snedecor and Cochran (1978), and Steel and Torrie (1980). Unfortunately, these techniques are not suited for experiments in which the treatments are graded levels of quantitative treatments. Petersen (1977) showed that pairwise multiple comparison procedures are seldom appropriate for experiments with structured quantitative treatments, such as experiments for determining crop production functions. Instead, regression techniques or orthogonal contrasts should be used.

Draper and Smith (1981) present general guidelines for assessment of the optimal number of plots for experiments with structured quantitative treatments used for determination of production functions. No technique was found, however, to assess the optimal number and size of plots for detection of the shape of a production function with confidence intervals of specified length, nor for detection of a difference between the shapes of two production functions.

This paper presents a technique for evaluating the optimal number and size of plots in experiments with structured quantitative treatments. The technique is illustrated with a water production function of trickle-irrigated chile peppers.

THEORY

Relation between Plot Size and Plot Variance

Smith (1938) developed an empirical relationship between plot size and plot variance

$$s_x^2 = s_u^2/x^b \qquad [1]$$

where

s_x^2 = variance of yield per unit area among plots of size x units,
s_u^2 = variance of yield per unit area among plots having unit area,
b = coefficient which indicates dependency between plots, and
x = number of unit plots in the plot under consideration.

The limiting values of coefficient b are zero and one: if the x units are identical (perfectly correlated) then $b = 0$, and if the plot is composed of a random selection of x units, $b = 1$. The latter case gives the formula for the variance of the mean of x independent units.

Contrasts

The use of contrasts in experiments is described by several authors: Freund (1974), Little and Hills (1978), and Steel and Torrie (1980). Consider a research situation with k treatments indexed by $i = 1, 2, \ldots, k$ and having population means denoted by μ_i. Many interesting functions of the μ_i such as $\mu_1 - \mu_3$, $(\mu_2 + 2\,\mu_4 + \mu_5)/4$, etc., can be expressed by a linear combination of the form $\Sigma c_i\,\mu_i$; typically, the c_i are taken to be integers. If $\Sigma c_i = 0$, the linear combination is called a contrast because the absolute size of the μ_i's add

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Soil Physical and Morphological Properties and Root Growth

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Soil provides the physical space and the resources to support root growth. The water and nutrients needed for the growth of both roots and the aerial portions of the plant are housed in soil pores. The size and distribution of pores in a soil determine its ability to store and transmit these entities to the roots. Other physical properties of soil, such as texture, structure, temperature, aeration and water content, also influence root growth.

Roots elongate in the soil when root pressure exceeds soil mechanical impedance. Root elongation is affected by the nature of the soil profile. Roots proliferate in the biopores made by soil fauna, such as earthworms, or in old root channels made by previous crops. On the other hand, a hardpan layer in the soil profile or a high water table restricts root growth. Soil management practices modify soil physical properties and significantly impact root growth. Tillage can alter soil porosity by loosening soil particles and breaking up aggregates. Heavy machines used for tillage, harvesting, and other cultural practices can compress soil pores by compacting the soil.

The purpose of this paper is to discuss the various physical and morphological properties of soil that influence root growth. Soil and crop management practices that alter these properties in relation to root growth are also analyzed.

SOIL PHYSICAL PROPERTIES

Bulk density and porosity

Bulk density and porosity are interrelated. As bulk density increases, total porosity decreases. Lateral or horizontal variation in bulk density results from changes in soil texture, structure, organic matter concentration and management practices, whereas vertical variation is the result of soil morphology. Seasonal changes in bulk density can result from freezing and thawing, raindrop impact, soil settling and biological activities (Cassel, 1982).

Bulk density or porosity is altered by tillage, traffic or the addition of organic matter. Kaspar et al. (1991) obtained higher bulk density in the surface soil in no-till than in chisel-plow or ridge-till system. Kaspar et al. (1995) found a bulk density of 1.36 $Mg \cdot m^{-3}$ in trafficked vs. 1.09 $Mg \cdot m^{-3}$ in nontrafficked interrows. Taylor (1983) observed that 75% of the increase resulted from the first traffic pass, although subsequent passes also increased bulk density. Zhang et al. (1997) reported a negative linear relationship between the amount of organic matter added and bulk density. Sainju and Good (1993) observed lower bulk density in the surface soil than in subsoil in an undisturbed forest because of the plant litter (organic matter) deposit on the surface.

Both high bulk density and low porosity restrict root growth. Rosolem and Takahashi (1996) reported a 10% and 50% decrease in soybean [*Glycine max* (L.) Merr.] root growth when the bulk density of a dark red Latosol (70% sand and 22% clay) was increased from 1.06 $Mg \cdot m^{-3}$ to 1.45 and 1.69 $Mg \cdot m^{-3}$, respectively. Foil and Ralston (1967) found that root growth of loblolly pine (*Pinus echinata* Mill.) was severely restricted when bulk density was >1.4 $Mg \cdot m^{-3}$. Shierlaw and Alston (1984) observed that bulk density equal to or >1.2 $Mg \cdot m^{-3}$ reduced root growth in corn (*Zea mays* L.) seedlings. As soil bulk density increased, root length decreased and root diameter increased in corn seedlings (Logsdon et al., 1987b) (Fig. 1). Sainju and Good (1993) found a negative relationship between root length density and bulk density and a positive relationship between root length density and porosity.

Aeration and water content

Soil should contain more than 10% air-filled pores to maintain aeration (Box, 1996; Grable and Siemer, 1968). Pores not filled with water are filled with air. Intensity of rooting is restricted by deficient aeration. Gardner and Danielson (1964) found a high correlation ($r = 0.998$) between soil penetration by cotton (*Gossypium hirsutum* L.) roots and percentage of aeration porosity. Root elongation is more sensitive to oxygen diffusion rate (ODR) than to oxygen concentration. When ODR in the soil falls below 58 $mg \cdot m^{-2} \cdot s^{-1}$, root growth is restricted (Erickson and Van Doren, 1961). Compacted soil may have ODRs of <33 $mg \cdot m^{-2} \cdot s^{-1}$ (Erickson, 1982). Therefore, in compacted soil, even air-filled pore space >10% can limit root growth. Asady et al. (1985) reported that root penetration of compacted layers decreased linearly as air-filled porosity decreased from 30% to 0%.

Drought conditions result in deeper root penetration and higher root distribution in the subsoil than in the surface soil. Box et al. (1989) found that drought decreased root counts in corn by 37% in the 0- to 20-cm depth, but at 60- to 150-cm depth, root counts were 50 times higher after an 18-d drought period in comparison with well-irrigated plants. Similarly, plants growing on xeric and subxeric (dry) sites have higher root densities than those growing on mesic (moist) site (Kalisz et al., 1987; Parker and Van Lear, 1996; Sainju and Good, 1993). However, soil drying increases mechanical resistance and can restrict root growth. On the other hand, soil wetting decreases interparticle attraction and increases particle mobility, which, in turn, decreases the pressure needed for soil deformation (Bennie, 1996). Details of soil water effects on root system is the topic of an accompanying paper of this workshop proceedings.

Temperature

Temperature at the soil-atmosphere interface controls soil temperature. However, it is moderated by soil color, surface random roughness, surface residue, and soil moisture content (Box, 1996). Soil temperature influences root biomass (Voorhees et al., 1981; Walker, 1969), elongation rate (Logsdon et al., 1987b), and rate of branching (Box, 1996). The maturation zone occurs closer to root apex and root orientation becomes horizontal at low temperature (Box, 1996). As temperature increases, root angle from the vertical decreases (Sheppard and Miller, 1977). Soil temperature is discussed comprehensively in another paper of this workshop proceedings.

Organic matter

Besides supplying nutrients to plants, organic matter also improves soil physical condition. It reduces bulk density, improves soil aggregation and infiltration capacity, and increases water-holding capacity. Soil containing adequate amounts of organic matter is less prone to compaction (Zhang et al., 1997). Unger and Kaspar (1994) reported that soil organic matter promoted earthworm activity; when organic matter was adequate, earthworms burrowed to a depth of up to 2 m, thereby forming macropores in the compacted soil. Earthworm burrows increased water movement and penetration of roots through otherwise less amenable soil horizons.

Organic matter promotes root proliferation. Root density is greater in horizons of the soil profile with higher organic matter accumulation (Davis et al., 1983; Kalisz et al., 1987; St. John, 1983). Sainju and Kalisz (1990) observed that, in eastern Kentucky's undisturbed forest soils, there were more roots in weathered coal seam (coal bloom) subsoil horizons containing higher organic matter concentrations than in adjacent colluvium horizons at the same depth. Similarly, Sainju and Good (1993) found higher root density in the soil horizon that contained a higher concentration of organic matter than in the horizons above and below it.

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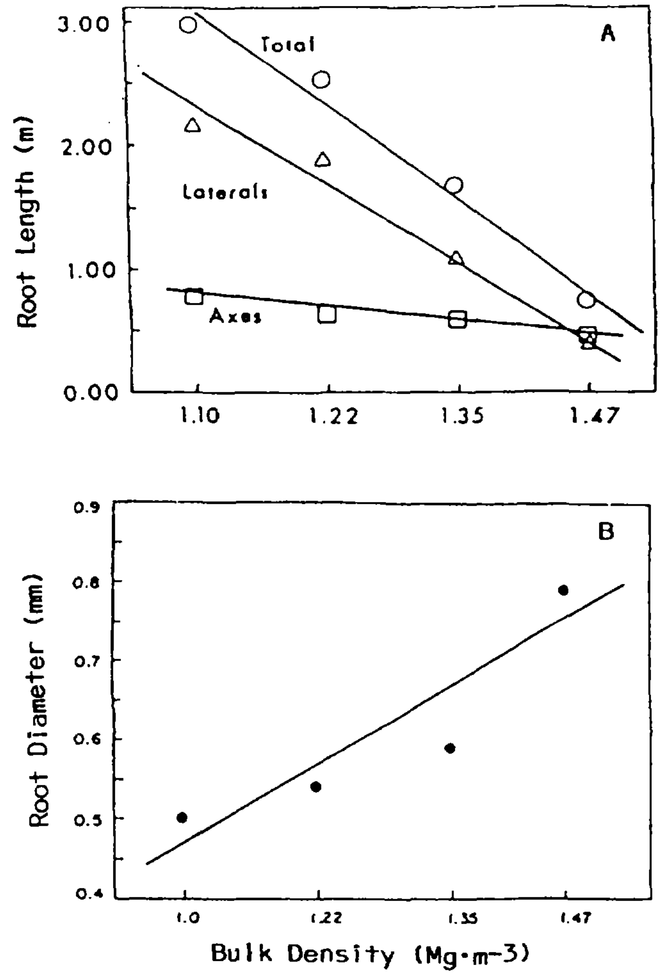

Fig. 1. Root length and diameter of 6-day-old corn seedlings as affected by bulk density (After Logsdon et al., 1987b).

Mechanical strength and impedance

Mechanical strength of a soil protects its pore space from collapse under the overlying weights. However, it also impedes root growth. Roots must apply a force greater than the mechanical strength of the soil matrix to elongate. Mechanical impedance depends on adhesive and cohesive forces of soil particles, that, in turn, depend on water content, texture, porosity or bulk density, pore size distribution, organic matter content, aggregate size, overburden pressure and degree of confinement, exchangeable cations, degree of cementation, orientation of soil particles, and surface roughness of sand particles (Bennie, 1996). Soil impedance increases from excessive animal grazing, use of heavy farm and tillage equipment, vehicular traffic, saturation of sandy topsoil during flood irrigation, and settling of soil particles. As bulk density of soil changes seasonally, mechanical impedance also changes (Cassel, 1982).

After reviewing the literature, Unger and Kaspar (1994) concluded that root growth of most species slows considerably or completely ceases at soil impedance above 2.0 MPa penetrometer resistance. Root elongation rate or root length varies inversely with, whereas mean root diameter is directly proportional to, mechanical impedance (Bennie and Krynauw, 1985; Greacen, 1986; Misra et al., 1986b). Mechanically impeded roots are shorter, thicker, and more irregularly shaped than are roots growing under low strength condition (Dexter, 1986a, 1986b; Richards and Greacen, 1986). They also have significantly fewer second- and third-order lateral roots (Sauerbeck and Helal, 1986). Bennie and Burger (1981) found that relative root length (root length per pot/maximum root length) in maize, cotton, wheat (*Triticum aestivum* L.), and groundnut (*Arachis hypogaea* L.) decreased curvilinearly with increasing soil strength (Fig. 2).

The relationship between soil impedance and root growth has been described by Klepper and Rickman (1990) as:

$$(1/L)(dL/dt) = \phi\ (P\text{-}Y\text{-}M)$$

where L is root length (m), ϕ is wall extensibility ($S^{-1}\cdot MPa^{-1}$), P is turgor pressure of root cells for extension (MPa), Y is the minimum turgor pressure required for expansion (MPa), and M is the resistance of soil to root penetration (MPa).

Dexter (1987) proposed the following exponential equation to describe the effect of impedance on root elongation:

$$R = R_{max}(e^{-0.6931})(Q_p/Q_{0.5})$$

where R is the root elongation rate ($m\cdot d^{-1}$), R_{max} is the maximum root elongation at very low impedance ($m\cdot d^{-1}$), Q_p is the penetrometer resistance (MPa) and $Q_{0.5}$ is the penetrometer pressure corresponding to $(R/R_{max}) = 0.5$.

The ability of roots to penetrate impeding soil layers varies among plant species. Wolfe et al. (1995) compared the root growth of cabbage (*Brassica oleracea* L. Capitata group), cucumber (*Cucumis sativus* L.), snap bean (*Phaseolus vulgaris* L.), and sweet corn at low (<1 MPa) and high (>2 MPa) penetrometer resistance soil strengths. Root growth of all species was slower in high strength than in low strength soil. However, the reduction ranged from 43.6% in sweet corn to 77.9% in cucumber. Winter wheat and sunflower (*Helianthus annuus* L.) roots can penetrate >2.0-m depth in Pullman series soil (fine, mixed, thermic Torrertic Paleustolls), while grain sorghum [*Sorghum bicolor* (L.) Moench] roots are mostly confined to the upper 1.2 m (Eck and Taylor, 1969; Johnson and Davis, 1980; Jones, 1978). Elkins (1985) found that bahiagrass (*Paspalum notatum* Flugge var. Pensacola) roots penetrated soil layers that were impermeable to cotton roots. Alfalfa (*Medicago sativa* L.), sweetclover (*Melilotus alba* Medik), and guar [*Cyamopsis tetragonoloba* (L.) Taubert] roots also have the ability to penetrate compact soil layers (Bowen, 1981).

Once a root penetrates through the compacted soil, it makes channels and macropores that facilitate subsequent rooting. Elkins et al. (1977) observed cotton root growth through the compact soil horizon for three consecutive years when planted after bahiagrass.

SOIL MORPHOLOGICAL PROPERTIES

Soil profile

Soil profile varies with location because of the differential effects of various factors of soil formation, such as parent material, vegetation, climate, and time. Not only does the depth of a horizon in the profile change within a few meters, but the physical, chemical and biological properties of the soil also vary. As a result, root distribution differs with location. Root development and distribution differ not only among plant species (Kasperbauer, 1990; Klepper, 1992; McMichael, 1990; Zobel, 1992), but also within species because of the differences in soil environmental conditions where roots grow (Jung, 1978; Kasperbauer, 1990). Some of these soil conditions are soil structure, mineral stress, temperature, gases, drainage, and availability of nutrients and water. All or some of these conditions may

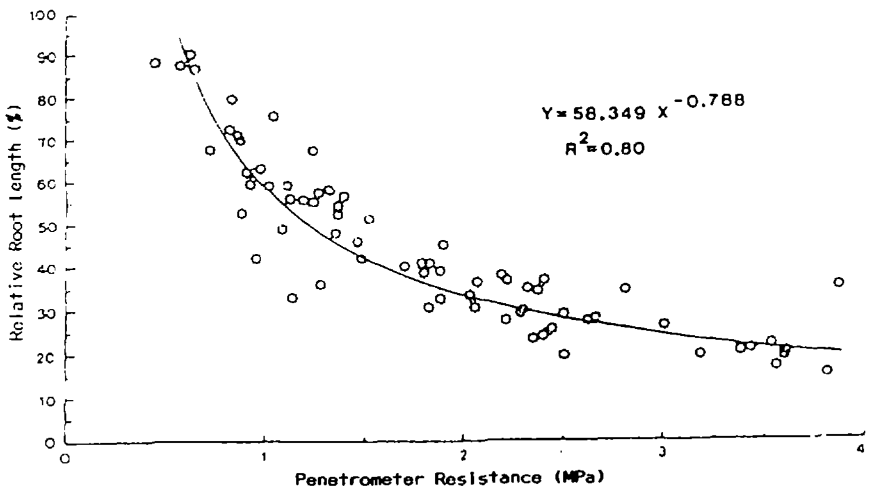

Fig. 2. Effect of soil impedance on relative root length of 70-day-old maize, cotton, wheat, and groundnut plants (After Bennie, 1996). Regression equation based on combined data for all four species.

interact with the genetic character of the plant (Box, 1996). Root elongation and branching may be extensive in a favorable environment, whereas growth is substantially reduced in an unfavorable environment (Hamblin, 1985). These variations in soil environment and root growth occur not only from one soil layer to another but also within a given layer (Box, 1996).

Root density usually decreases with depth (Kalisz et al., 1987; Klepper and Rickman, 1990). The highest concentration of roots, especially fine roots, occurs near the soil surface where conditions are more favorable for root growth. These layers are usually rich in organic matter, nutrients, cation exchange capacity, and porosity, and low in bulk density (Sainju and Good, 1993). Fine roots constitute a large proportion of total root biomass and are therefore important in water and nutrient absorption (Parker and Van Lear, 1996). On the other hand, large roots, such as tap and sinker roots, penetrate deeper into the profile to access moisture when the surface layer dries, and also to support aboveground plant biomass. Kalisz et al. (1987), Sainju and Good (1993), and Sainju and Kalisz (1990) found an exponential decline in root density with soil depth, reflecting declining fertility, reduced organic matter concentration, and decreasing aeration.

The presence of a hard layer, such as fragipan, duripan, argillic or alluvial horizons, within a soil profile severely restricts root growth. These layers are formed by settling of sand and clay particles and cementation between them during soil formation. Such layers can occur at any depth in the soil profile. Root growth in these layers depends on water flux and water content, as well as on the frequency of cracks, planar voids, biopores, and packing voids, and on pedal properties (Box, 1996). Sainju and Good (1993) found reduced root density in the B horizon of New Jersey Pineland forest soils whenever a firm argillic layer was present in this horizon. On the other hand, when the B horizon was higher in nutrient concentrations and cation exchange capacity than adjacent horizons, it promoted greater root density than layers immediately above and below it.

Biopores

Biopores are formed by decaying plant roots, mesofauna (such as earthworms), or cracks within the horizon when the soil dries during the drought condition. These pores are usually filled with loose surface soil or decaying organic matter or both, allowing easier root penetration (Parker and Van Lear, 1996). Soils in the biopores are often characterized by enhanced fertility, and better aeration and moisture conditions that promote vigorous root growth (Lutz and Chandler, 1955; Van Rees, 1984). In addition, biopores form as avenues for water and air flow in heavy-textured subsoils that have restricted permeability (Anderson and Bouma, 1976; Quinsberry et al., 1993).

Parker and Van Lear (1996) reported that there were 0 to 8 old root channels/m^2 soil profile area in mature loblolly pine stands in Piedmont soils, with size ranging from 69 to 105 cm^2. They also noted that density of fine roots in old root channels was 17 times as high as in the adjacent soil matrix. Therefore, although biopores constitute a small area of the soil profile, they are important avenues for root growth, especially in dense layers, because of the high concentration of roots in them. Biopores often extend more deeply into the soil than do cracks (Van Stiphout et al., 1987).

Soil–rock interface

Rocks may act as loci for water films that promote root proliferation in the soil–rock interface. They also may contain macropore spaces from prior biological activity that allow root penetration. Parker and Van Lear (1996) found that the number of rock–soil interfaces were as high as 13/m^2 soil profile area and that root density in the interface was significantly higher than in the adjacent soil matrix.

Water table

The presence of a shallow water table in the soil profile restricts root growth unless roots can grow in anaerobic conditions, and limits the volume of the soil available for exploitation by roots. In such a case, roots grow profusely above the water table (Gary, 1962; Oliver 1978). Sainju and Good (1993) found higher root density in the soil layer just above the water table than in higher layers in pine-oak lowland forests in New Jersey.

SOIL AND CROP MANAGEMENT PRACTICES

Tillage

Tillage can alter soil bulk density, porosity, aggregation, and mechanical impedance and therefore affect root systems. It can mix and granulate the soil, eradicate or control plants, incorporate plant residues and chemicals, and establish desired surface configuration and degree of compactness for root growth (Gill and Vanden Berg, 1967). Kaspar et al. (1991) found that a no-till system produced higher bulk density than chisel-plow or ridge-till systems. According to Bauder et al. (1981), reduced or no-till systems could lead to an increase in the development of root-restricting soil layers in a clay loam soil. Voorhees (1983) hypothesized that increased bulk density in a no-till system could be an effect of incomplete amelioration of compacted soil over the winter.

The effect of tillage on root distribution system is variable. Kaspar et al. (1995) observed no significant differences in root length density between no-till, ridge-till, and chisel-plow systems. Baligar et al. (1996) obtained greater root length per plant and root density in silage corn in a no-till system than in a conventional-till system. In contrast, Bauder et al. (1985) observed that root length density in the 0- to 30-cm depth was higher in a ridge-till system than in no-till or chisel-plow systems. Bhagat and Acharya (1987) also found higher root density in the root-restricting soil layer with mulched conventional tillage than with nonmulched conventional tillage or no-tillage systems in a monsoonal climate. Rasse and Smucker (1996) reported maximum root growth for alfalfa and corn in the in the upper B_t and B_{t2} soil horizons under no-till and conventional-till, respectively.

In our study on the effect of tillage on tomato (*Lycopersicon esculentum* Mill.) root distribution in a Dothan sandy loam soil (Plinthic Paleudult) in Georgia, the number of roots/cm^2 soil profile from 19.5- to 58.5-cm depth was 65% higher in a moldboard-plowed system than in no-till (Fig. 3); the higher root number was attributed to less soil impedance. However, Merrill et al. (1996) found that in dryland cropping, root length density of spring

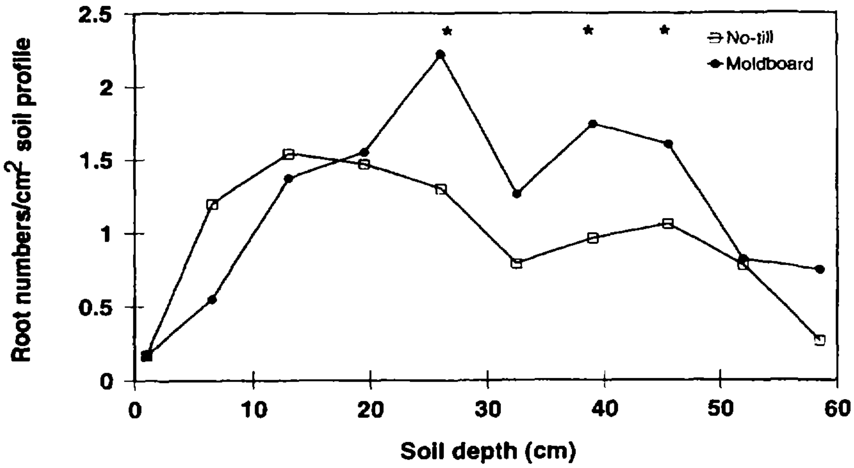

Fig. 3. Tomato root distribution at various soil depths 90 d after transplanting as affected by no-till and conventional-till. *Differences between systems significant at $P = 0.05$.

wheat was 40% to 112% higher in a no-till than in a conventional-till system. They attributed this to superior moisture conservation and cooler soil temperature in the near-surface zone in no-till under dryland farming conditions.

Tillage management assumes special importance in soils with naturally dense horizons. Bowen (1981) recommended plowing at or near a soil water potential of −1.5 MPa to shatter a compacted soil layer. The water contents for clay, sandy clay loam, and loamy sand at this water potential are in the range of 0.35 to 0.40, 0.22 to 0.25, and 0.08 to 0.10 $cm^3 \cdot cm^{-3}$, respectively (Gupta and Larson, 1979). In coarse-textured southeastern Coastal Plains soils, corn and tobacco (*Nicotiana tabacum* L.) formed more roots below the compacted layer with in-row subsoiling than without subsoiling (Vepraskas et al., 1986; Vepraskas and Wagger, 1990). Cary et al. (1967) obtained increased root number and water extraction, and doubling of alfalfa hay yields, as a result of loosening and mixing of B horizon of Freeman silt loam (Mollic Palexeralf). Rosolem and Takahashi (1996) obtained a quadratic decrease in the soybean root growth by increasing the subsoil bulk density of a dark Latosol (70% sand and 22% clay) soil column from 1.06 to 1.71 $Mg \cdot m^{-3}$. However, the root growth was not completely inhibited even at the highest bulk density. Once roots penetrated the compacted layer, growth was completely restored.

Traffic

Use of heavy farm machinery for tillage, cultural operations, harvesting, and transport causes soil compaction. The soil properties and processes affected by soil compaction include increased bulk density and mechanical resistance, disruption of pore continuity, and altered exchange of water, heat and gas (Assouline et al., 1997; Linn and Doran, 1984; Wierenga et al., 1982). Large pores conducting water at lower tension are more easily destroyed than smaller ones conducting water at higher tensions (Ankeny et al., 1990). Small aggregates are less compacted by traffic than are large aggregates (Logsdon et al., 1987a; Misra et al., 1986a, 1986b).

Bauder et al. (1985) and Gerik et al. (1987) found that the bulk density and soil strength on the trafficked side of a row was much greater than on the nontrafficked side of the same row. Kaspar et al. (1995) observed that the hydraulic conductivity near saturation in a Webster silt clay loam (Typic Haplaquoll) was 39.4 and 104.7 $mm \cdot s^{-1}$ in trafficked and nontrafficked interrows, respectively. Soil compaction from traffic is a serious problem in no-till and ridge-till systems (Karlen, 1990). Limiting traffic to permanent traffic lanes is suggested as a way of reducing compaction (Taylor, 1983). Raghavan et al. (1979) observed maize root densities of 5.7 vs. <2 $mg \cdot g^{-1}$ in the upper 20 cm of soil with no traffic vs. 15 passes of 62-kPa tire track, respectively. Root length density in barley (*Hordeum vulgare* L.) in the top 30 cm of the soil decreased as the number of tractor passes over the field increased from zero to six (Willatt, 1986). Voorhees et al. (1989) reported that compaction of the subsoil with an 18-Mg axle load decreased root growth of corn below 45 cm more than did a <4.5-Mg axle load. Dolan et al. (1992) observed that compaction of the subsoil of Webster clay loam (Typic Haplaquolls) reduced corn P and K uptake as much as 22% when June and July rainfall was less than average.

Kaspar et al. (1991) found that root length and root mass of corn in the 0- to 15-cm layer of trafficked interrows was one-third and one-half, respectively, of that in nontrafficked interrows. Traffic also reduced root growth in the 15- to 30-cm soil layer, but the differences between trafficked and nontrafficked interrows were not as large as those for 0- to 15-cm layers. Kaspar et al. (1995) reported that root length density in a particular interrow was also affected by traffic pattern in the adjacent interrows. Chaudhary and Prihar (1974) noted that interrow compaction resulted in downward movement of roots because of inhibition of lateral root elongation. Hilfiker and Lowery (1988) observed that the response of root growth to wheel tracks depended on both soil type and tillage system. Bauder et al. (1985) reported that tillage had a greater effect on root length than did wheel traffic.

Crop rotation

Crop rotation can improve soil physical condition by adding more biomass residue to the soil in comparison with a continuous single crop (Bullock, 1992; Havlin et al., 1990; Hussain et al., 1988; Juma et al., 1993). Incorporation of biomass results in improved soil structure (Kay, 1990) and aggregation (Raimbault and Vyn, 1991; Van Bavel and Schaller, 1950), lower soil bulk density (Bullock, 1992; DeKimpe et al., 1982; Hageman and Shrader, 1979), increased water infiltration (Jordahl and Karlen, 1993; Logsdon et al., 1993), higher water retention capacity (Hudson, 1994; Jamison, 1953), improved soil aeration and reduced soil erosion (Bezdicek, 1984; Reganold, 1988; U.S. Dept. of Agriculture, 1980). The effects of physical properties on root proliferation have already been described.

Elkins (1985), Kay (1990), and Merrill et al. (1994) observed that including a deep-rooted crop in the rotation increased biopores in the soil that facilitated proliferation of the roots of the succeeding crop. Merrill et al. (1996) found that spring wheat planted after sunflower had greater root density in no-till than in conventional-till. Since the soil was not disturbed in no-till, in all probability, biopores made by the deep roots of sunflower remained intact for the succeeding wheat roots to recolonize, thus facilitating formation of more roots than was the case for conventional-till. Rasse and Smucker (1996) reported that in a corn-alfalfa succession, alfalfa roots recolonized 14% and 21% of corn root-induced macropores in B_t horizon under conventional-till and no-till, respectively. Root recolonization in the B_{t2} horizon was 17% and 18% for conventional-till and no-till, respectively.

SUMMARY

Root development in the soil is influenced by soil physical properties as well as the nature of horizons in the soil profile. Soils vary widely in their physical properties, and hence in their ability to support root growth. The presence of a hardpan or water table in the root zone impedes root growth. Roots proliferate in the soil horizons with favorable conditions, such as high organic matter content and abundant biopores. Roots of different crop species as well as of cultivars within species differ considerably in their ability to penetrate through hard soil layers. Management practices, such as tillage, traffic, and crop rotation can influence root growth by altering soil properties.

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Root Distribution Patterns of Nine Apple Rootstocks in Two Contrasting Soil Types

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Abstract. **Root distribution of 'Starkspur Supreme Delicious' on nine apple (*Malus domestica* Borkh.) rootstocks grown in two different soil types in the 1980 NC-140 Uniform Apple Regional Rootstock Trial (Michigan and Ohio sites) was determined using the trench profile method. Based on the number of roots counted per tree, rootstocks could be separated into five groups for the Marlette soil from most to least: MAC.24 > OAR1 > M.26EMLA = M.9EMLA > M.7EMLA = O.3 = M.9 = MAC.9 > M.27EMLA. For the Canfield soil, rootstocks were ranked for number of roots counted from most to least as follows: MAC.24 > OAR 1 = MAC.9 = M.7EMLA > M.26EMLA = O.3 = M.9 EMLA = M.9. Root distribution pattern by depth was affected by soil type with roots fairly well distributed throughout the Marlette soil but restricted primarily above the fragipan in the Canfield soil. Two rootstocks performed differently from others in adapting to soil conditions at the different sites. MAC.9 had the second lowest number of total roots/dm^2 in the Marlette soil yet the second most in the Canfield soil, while the opposite was found for M.9EMLA. Regression analysis demonstrated positive correlations between number of roots counted and vigor and yield of the scion.**

The NC-140 Technical Committee was established in 1967 with the central objective of facilitating cooperative research on new rootstocks and their adaptability to environmental conditions of different North America regions (Ferree and Perry, 1988). Cooperators agreed to follow the Technical Committee's planting design and cultural guidelines for tree training and support, thinning, and fertilizing as well as to collect specific data. Cooperators were encouraged to collect additional data on specific interests such as those reported in this study. The 1980 NC-140 Uniform Apple Regional Rootstocks Trial consisted of 'Starkspur Supreme Delicious' (*Malus domestica* Borkh.) on nine rootstocks of varying size. Rootstock vigor listed from least to most dwarfing for the Michigan and Ohio plantings were as follows: MAC.24, M.7 EMLA, OAR1, M.26EMLA, Ottawa 3 (O.3), M.9EMLA, M.9, MAC.9, and M.27EMLA with OAR1 being more dwarfing than M.26EMLA and M.9 more dwarfing than MAC9 in Ohio (NC-140, 1991).

Physical characteristics of soil have been found to influence root growth and distribution patterns (Cockroft and Wallbrink, 1966; Oskamp, 1932; Rogers and Vyvyan, 1934; Taylor and Gardner, 1963). Root systems may be confined to areas above hardpans with high soil bulk densities due to the inability of roots to penetrate them (Eavis and Payne, 1968, Greacen et al., 1968). Knowledge of root distribution patterns under various soil conditions is important to aid in rootstock selection. Trees with root systems capable of penetrating fragipans or adapting to other adverse soil condition, need to be identified for use in such situations. The ability of root systems to adapt to soil environments is important when selecting rootstocks for orchards and experimental plots. Preliminary data on the overall rooting intensity and percent distribution of root size categories was requested for inclusion in volume 45 of *Fruit Varieties Journal*, which contained summary reports of this NC-140 rootstock trial (Fernandez et al., 1991). This paper will report on root distribution patterns, soil characteristics of the sites and relationships between rooting intensity, and scion vigor and yield. The objectives of this study were to describe the root distribution pattern of nine clonal apple rootstocks at two NC-140 trial locations with highly different soil characteristics, determine root adaptation to soil environment, including soil type and soil impedance, and determine the relationship of scion growth and yield parameters to root system characteristics.

Materials and Methods

The 1980 NC-140 Uniform Apple Regional Rootstock Trial consisted of 'Starkspur Supreme Delicious' propagated on nine rootstocks. Sites located at Michigan State Univ., East Lansing and Ohio State Univ., Ohio Agricultural Research and Development Center, OH were used for this study based on the contrasting soil types and conditions. Trees were planted with a 3.5 m within-row and 5.5 m between-row spacing with north to south row orientation and 1 m wide herbicide strip in a randomized complete block with five single tree replicates. Trees were trained to a central leader without support and received similar management practices at both sites.

The soil series in Michigan was a Marlette fine sandy loam (Fine-loamy, mixed, mesic Glossoboric Hapludalfs) moderately well drained with moderate to moderately slow permeability (Anonymous, 1979). The soil series in Ohio was a Canfield silt loam (Fine-loamy, mixed, mesic Aquic Fragiudalfs) with a fragipan 60 to 70 cm below the soil surface with moderate permeability characterizing the soil above the fragipan and poor permeability through the fragipan (Anonymous, 1981). Soil bulk densities for each location were determined by sampling intact soil cores of a known volume in the trenches dug for counting roots. Soil core

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volumes were 350 and 230 cm^3 for the samples from the Marlette and Canfield soils. Ten soil cores were taken for each soil horizon (six for Marlette and five for Canfield) within the 1.2 m from the soil surface that corresponded to the vertical height of the root counting frames described below. Each horizon was assumed to have the same bulk density throughout based on field observation and characteristics reported in the soil surveys (Anonymous, 1979, 1981). Specific information on soil characteristics can be found in the soil surveys.

Roots were counted using the profile wall method because of the ability to investigate root distribution with soil profile characteristics (Layne et al., 1986; Oskamp and Batjer, 1932; Perry et al., 1983). Excavation began 9 Oct. 1989 in Ohio and 30 Apr. 1990 in Michigan. Since the highest proportion of roots are found within 1 m from the center of the trunk of apple trees (Atkinson, 1980), trenches were excavated with a backhoe parallel to tree rows within the herbicide strip 0.8 m from the center of the trunks on east and west sides of the tree. The most common range for depth of rooting of apple is from 1 to 2 m (Atkinson, 1980), therefore, the trenches were 1.5 to 2 m deep. Root counting frames were constructed 1.2 m vertical height × 1.8 m wide and divided with cotton string into mapping grid squares of 15 cm vertical height × 30 cm wide. The soil on the face of the trench was loosened an additional 5 cm deep perpendicular to the soil profile and washed with a high pressure water gun to expose roots. Counting frames were placed over the washed profiles with the top level with the soil surface and centered on the trunks. Roots were counted and sized on corresponding paper grids as described by Layne et al. (1986) to a depth of 1.2 m from the soil surface and 0.9 m to the north or south of the center of the tree trunk. Roots were counted for all surviving replicates of each rootstock (five for MAC.24, OAR 1, M.9 EMLA, M.7 EMLA, MAC.9, M.27 EMLA and four for M.26 EMLA, O.3 and M.9 on the Marlette soil; five for MAC.24, OAR 1, M.26 EMLA, MAC.9; four for M.7 EMLA, O.3, M.9; and two for M.9 EMLA on the Canfield soil). Roots were classified into total roots and three size categories: less than 2 mm (small), 2 to 5 mm (medium), and greater than 5 mm in diameter (large) and expressed per dm^2 trench wall surface area. Tree height, canopy spread, trunk cross-sectional area (TCA), yield and yield efficiency were recorded as required by the NC-140 technical committee (NC-140, 1991).

Analysis of variance was conducted using the PROC GLM procedure of the SAS statistical program (SAS Institute, Cary, N.C.). Data from each location were analyzed separately as randomized complete blocks. The analysis of variance for the root mapping indicated little to no effect on root numbers due to the east or west facing profile of the tree or due to distance north or south in the row from the center of the trunk (data not shown), therefore, both profiles and all distances were combined for analysis for each tree. Data were analyzed to determine the relationship between number and size of roots at each depth by rootstock and presented as numbers of roots/dm^2 trench wall surface area. Differences in number of roots/dm^2 by depth also were analyzed for each rootstock.

Linear regression analysis for each location was conducted using the PROC REG procedure of the SAS statistical program to determine the relationships between the number of roots counted vs. vigor and yield components. Total number of small, medium and large roots were regressed against TCA, tree height, canopy spread, and yield data from 1989 and 10 year cumulative yield. Regression analysis also was performed for the above comparisons for number of medium and large roots combined, since the relationships with medium or large roots alone were found to have the highest coefficients of determination (R^2). Discussion of linear regression will be concerned with models involving total roots and those having the highest R^2s.

Results and Discussion

Soil bulk densities were higher for cores taken at an average depth of 59- to 64-cm and 103- to 108-cm compared to cores from 17 to 22cm and 33 to 38 cm for the Marlette soil with no other differences found (Table 1). Soil cores taken at an average depth range of 40 to 47, 51 to 58 and 66 to 73 cm had higher bulk densities than the cores taken at 12 to 19 cm for the Canfield soil (Table 1). In addition, soil cores taken at 51 to 58 cm had higher bulk densities than those taken at 26 to 33 cm for this soil. The bulk densities recorded for soil cores taken at the 66 to 73 cm depth range, the location of the beginning of the fragipan, were much higher than all other soil core depths for the Canfield soil. Although the highest bulk densities were similar for the Marlette and Canfield soils, the highest bulk density for the Canfield soil was reached at an average depth range of 66 to 73 cm while the Marlette soil showed one area of high bulk density at a depth range of 103 to 108 cm.

The nine rootstocks were ranked for rooting intensity (number of roots per trench wall surface area) based on the total number of roots/dm^2 over all depths (Table 2) for the Marlette soil as follows: MAC.24 > OAR1 > M.26EMLA = M.9EMLA > M.7EMLA = O.3 = M.9 = MAC.9 > M.27EMLA. For the Marlette soil, rooting intensity regardless of root size category generally followed the same order as for tree vigor except M.7EMLA which was ranked lower and M.9EMLA which was ranked higher in total number of roots/dm^2 than their tree vigor ranking.

Rootstocks were ranked according to rooting intensity based on the total number of roots/dm^2 over all depths (Table 2) for the Canfield soil as follows: MAC.24 > OAR 1 = MAC.9 = M.7EMLA > M.26EMLA = O.3 = M.9 EMLA = M.9. Trees on M.27EMLA were not included in the root mapping of the Ohio site since all but one replicate died before excavation due to severe winter frost heaving that exposed the root system and resulted in root injury and

Table 1. Depth and bulk density of soil horizons of the Marlette and Canfield soils. Soil core volume was 350 and 230 cm^3 in the Marlette and Canfield soils, respectively. Depth to the top and bottom of the soil core was measured from the soil surface.

Soil horizon	Depth of horizon (cm)[z]	Depth from top to bottom of core sample (cm)	Bulk density of core sample ($g \cdot cm^{-3}$)
		Marlette soil	
Ap	0–28	17–22	1.38
B&A	36–51	33–38	1.40
B21t	51–67	59–64	1.55
B22t	67–86	82–87	1.50
C1	86–106	103–108	1.58
C2	106–153	127–132	1.50
LSD[y]			0.14
		Canfield soil	
Ap	0–20	12–19	1.40
2Bt1	30–53	26–33	1.41
2Bt1	30–53	40–47	1.46
2Bt2	53–65	51–58	1.48
2Btx1	65–100	66–73	1.61
LSD[y]			0.06

[z]Depth of soil horizons as reported in Anonymous (1979, 1981).
[y]LSD at $P = 0.05$.

Table 2. Average number of roots/dm² over all depths for total roots and each size category for the Marlette and Canfield soils.

Rootstock	Marlette soil				Canfield soil			
	Total	Small	Medium	Large	Total	Small	Medium	Large
				Roots/dm²				
MAC.24	5.01	4.75	0.15	0.11	4.36	3.89	0.29	0.18
OAR 1	3.65	3.38	0.19	0.08	2.86	2.56	0.21	0.09
M.26 EMLA	3.07	2.93	0.10	0.04	2.13	2.02	0.07	0.04
M.9 EMLA	2.81	2.69	0.08	0.04	1.64	1.49	0.10	0.05
M.7 EMLA	2.17	2.04	0.08	0.05	2.41	2.18	0.14	0.09
O.3	2.02	1.91	0.08	0.03	2.07	1.86	0.12	0.09
M.9	1.88	1.79	0.06	0.03	1.62	1.50	0.08	0.04
MAC.9	1.76	1.68	0.07	0.01	2.73	2.58	0.11	0.04
M.27 EMLA	1.48	1.42	0.05	0.01	---	---	---	---
LSD[z]	0.30	0.29	0.02	0.02	0.55	0.50	0.05	0.03

[z]LSD at $P = 0.05$ comparing rootstock for each size category.

subsequent death (Warmund et al., 1991). As in the Marlette soil, rooting intensity for all root size categories followed the same ranking as for tree vigor except MAC.9 was ranked higher than expected for rooting intensity when compared to tree vigor ranking.

Root distribution throughout the soil profiled showed different patterns for rootstocks and soil types (Figs. 1 and 2). For the Marlette soil, total and small roots/dm² were fairly evenly distributed by depth (Fig. 1 A and B) with a moderate decrease in roots/dm² at the lowest depths with the exception of M.26EMLA, which showed an increase for the lowest depths. Most rootstocks, except MAC.24, MAC.9 and M.26EMLA, showed a slight increase in number of total and small roots/dm² at the 15 to 30 cm depth compared to the 0 to 15 cm depth. Medium roots/dm² showed a large decrease in number from the 30 to 45 cm depth and below and large roots/dm² from the 15 to 30 cm depth and below (Fig. 1 C and D). Only the most vigorous rootstocks, MAC.24, OAR1 and M.26EMLA, had an average number of large roots/dm² below the 15 to 30 cm depth that was significantly greater than zero.

The root distribution pattern for total roots/dm² in the Canfield soil was much more consistent across rootstocks (Fig. 2). All rootstocks showed a gradual decrease in number of total roots/dm² from the 0 to 15 cm depth to the 45 to 60 cm depth with a considerable decrease subsequently (Fig. 2A). There was up to an order of magnitude difference in roots in the depths above the 60 to 75 cm range compared to the depths from 60 to 75 cm and below. The depths from 60 to 75 cm and below roughly correspond with the location of the fragipan in the Canfield soil (Anonymous, 1981; Table 1). The same root distribution pattern was seen for small, medium and large roots/dm² as for total roots/dm² except for each larger root size category roots were restricted to shallower portions of the profile (Fig. 2 B and D). For small roots/dm² the pattern was identical to total roots/dm² with a large decrease from 60 to 75 cm and below (Fig. 2B), for medium roots/dm² there were virtually no roots from 45 to 60 cm depth and below, for most rootstocks (Fig. 2C) For large roots/dm² almost no roots were found from the 15 to 30 cm depth and below in most instances (Fig. 2D). MAC.24 typically maintained a higher number of roots/dm² to a greater depth than the other rootstocks while M.26EMLA, M.9EMLA, M.9 and MAC.9 usually had very sparse rooting below 45 cm, with the others intermediate.

Although statistical comparison between the two soil types cannot be conducted, the difference in ranking of the rooting intensity of the rootstocks can be used to estimate relative performance at the two locations. MAC.9 and M.9EMLA switched ranking for the two soil types. MAC.9 had the second lowest number of roots/dm² per tree in the Marlette soil, ahead of M.27EMLA only, yet the second highest in the Canfield soil, similar to OAR1 (Table 2). M.9EMLA was in the third highest grouping of number of roots/dm² per tree behind OAR1 in the Marlette soil but had the fewest roots/dm² per tree in the Canfield soil. Rooting intensity of M.7EMLA was ranked lower for the Marlette soil than the Canfield soil. This suggests adaptation of MAC.9 to heavy soils with M.9EMLA performing better in the Marlette soil and M.7EMLA performing poorly in the Marlette soil with the other rootstocks not affected by soil type as far as total number of roots.

Although rootstock affected number of roots/dm² and depth of rooting, the soil environment had more influence on the root distribution pattern by depth. Depth of rooting was restricted by the fragipan in the Canfield soil and most roots were in soil layers above 60 cm since highly compacted pans present a physical barrier that severely limit root penetration (Eavis and Payne, 1968; Greacen et al., 1968). Between 91% and 94% of the total roots/dm² were located in the 0 to 60 cm depths for trees in the Canfield soil. The high percent of roots closer to the soil surface in the Canfield soil likely was caused by soil restriction of rooting volume. Increases in percent of root in regions closer to the soil surface in soils that restrict rooting volume has been observed for several fruit crops (Cockroft and Wallbrink, 1966; Oskamp, 1932). There was no such restriction to root distribution in the Marlette soil and roots were distributed fairly evenly throughout the soil profile with a moderate decrease in roots/dm² with depth and, in some cases, no decrease until the lowest depth measured. Between 55% and 68% with an average of 60% of the total roots/dm² were found in the 0 to 60 cm depths for trees in the Marlette soil. Soil texture also may be involved since Rogers and Vyvyan (1934) found an increase in total weight of four Malling apple rootstock root systems from a heavy clay to a light sand to a loam. Several authors have found a rootstock soil interaction for various tree crops with rootstocks performing differently under the diverse soil types (Cockroft and Wallbrink, 1966; Greacen et al., 1968; Irizarry et al., 1981; Mikhail and El-Zeftawi, 1978; Oskamp and Batjer, 1932; Rogers and Vyvyan, 1934). This confirms the observation of this study regarding MAC.9 and M.9EMLA adaptation to soil environment.

Regression analysis showed strong positive correlations between number of roots (total roots and all size categories) vs. TCA, tree height and canopy spread ($P < 0.001$) but not yield in 1989 nor cumulative 10-year yield for the Marlette soil. The highest R^2s were obtained when large roots were used for the regression analysis for trees in the Marlette soil. The models for total roots and

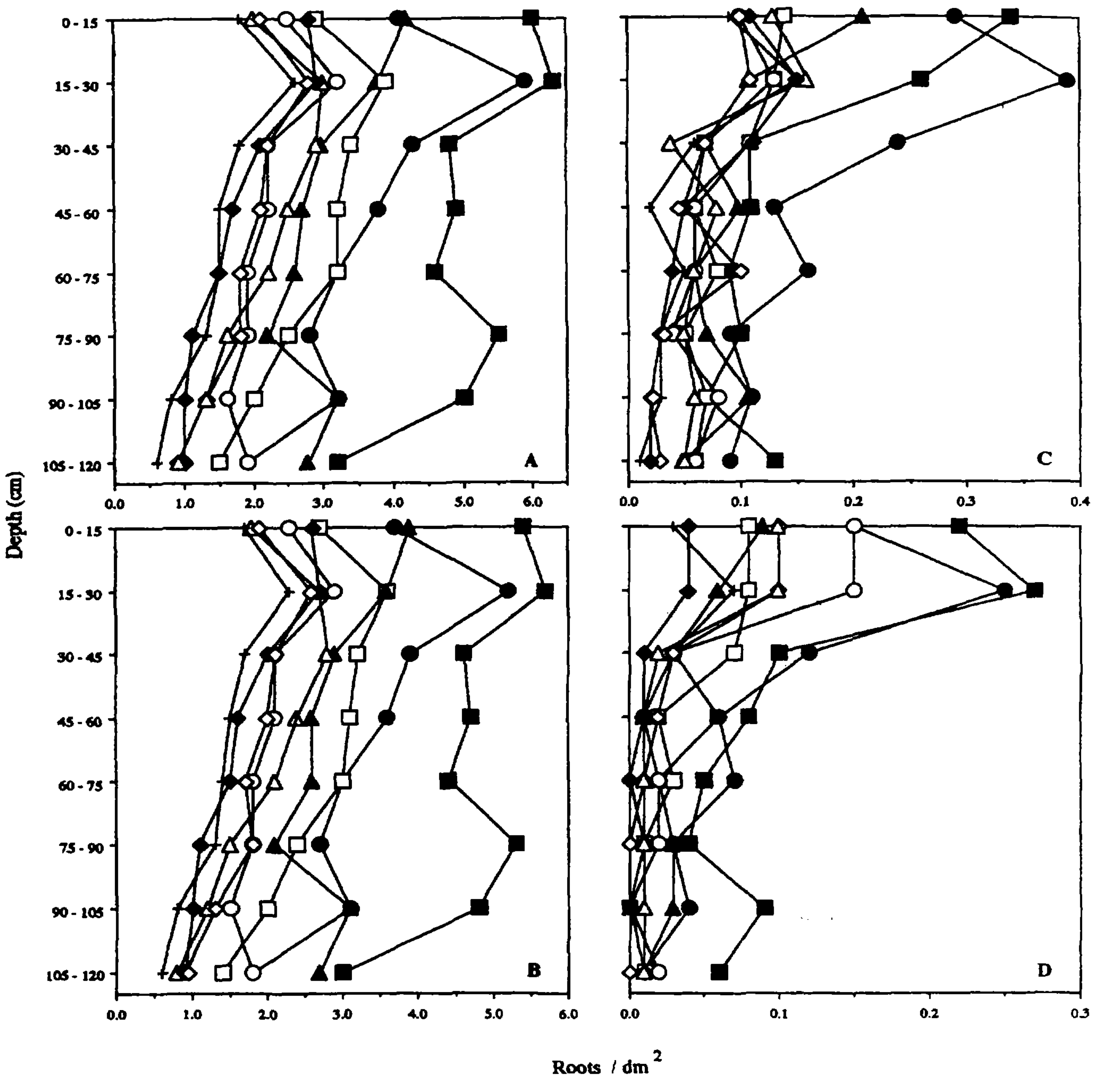

Fig. 1. Number of roots/dm² for each depth for the Marlette soil for total (A), small (B), medium (C), and large (D). LSD at $P = 0.05$ for comparison of rootstocks within depth for A and B (LSD identical for A and B), C, D, respectively: 0.90, 0.09, 0.07 for 0 to 15 cm and 15 to 30 cm; 0.80, 0.07, 0.04 for 30 to 45 cm; 0.80, 0.06, 0.03 for 45 to 60 cm; 0.70, 0.06, 0.03 for 60 to 75 cm; 0.70, 0.04, 0.03 for 75 to 90 cm; 0.90, 0.05, 0.03 for 90 to 105 cm; 0.70, 0.06, 0.02 for 105 to 120 cm. LSD at $P = 0.05$ for comparison of depth within rootstock: 1.3 for MAC.24 (■); 0.9 for OAR 1 (●); 1.0 for M.26EMLA (▲); 0.7 for M.9EMLA (□); 0.6 for M.7EMLA (○) and 0.3 (Δ); 0.5 for M.9 (light diamond) and MAC.9 (dark diamond); and 0.4 for M.27EMLA (+) .

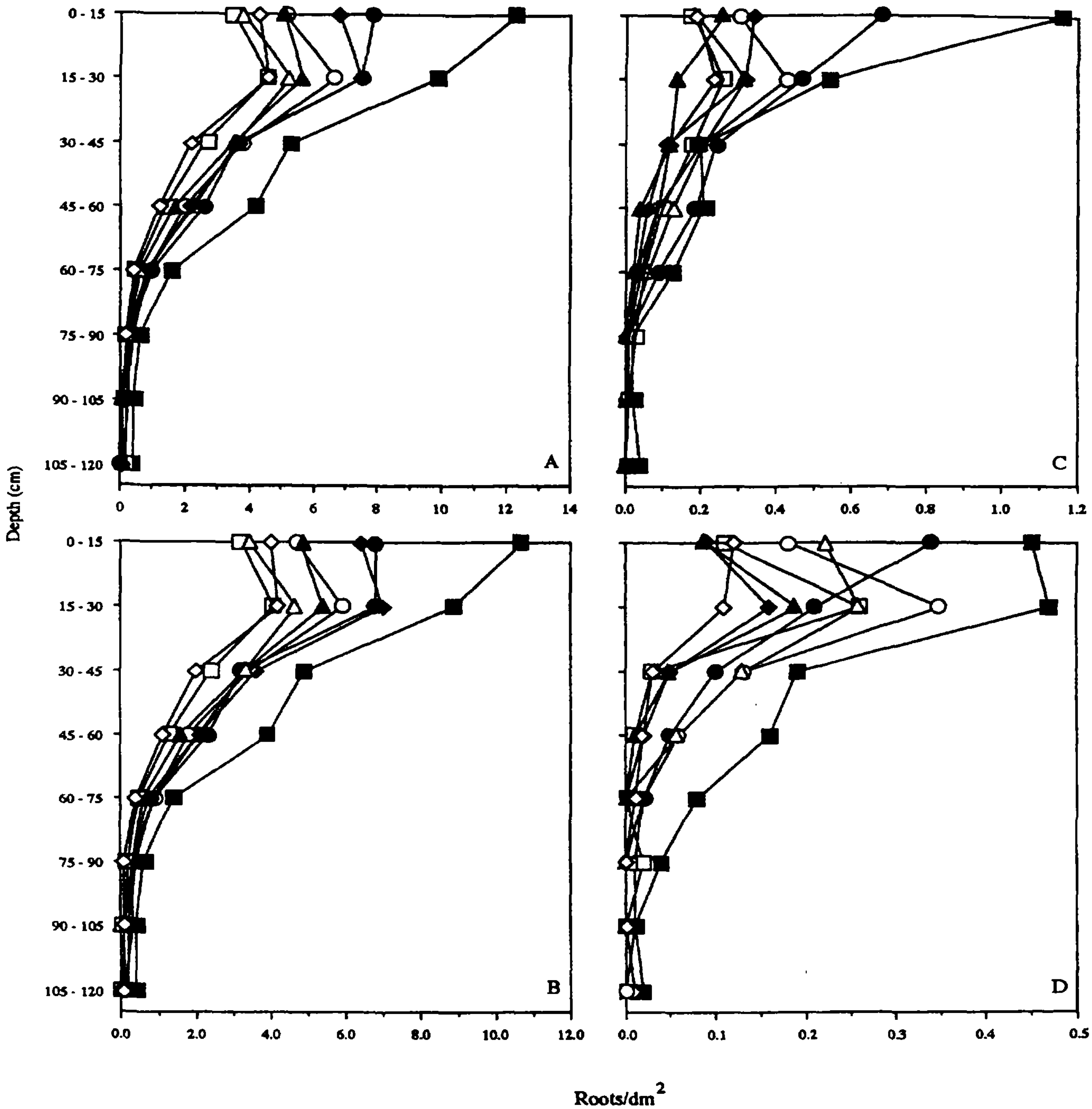

Fig. 2. Number of roots/dm² for each depth for the Canfield soil for total (A), small (B), medium (C), and large (D). LSD at $P = 0.05$ for comparison of rootstocks within depth for total (A), small (B), medium (C) and large (D) roots/dm² respectively: 2.40, 2.20, 0.22, 0.12 for 0 to 15 cm; 1.50, 1.40, .015, 0.12 for 15 to 30 cm; 0.90, 0.80, 0.10, 0.07 for 30 to 45 cm; 0.70, 0.70, 0.08, 0.05 for 45 to 60 cm; 0.40, 0.40, 0.06, 0.03 for 60 to 75 cm; 0.10, 0.20, 0.02, 0.02 for 75 to 90 cm;0.10, 0.10, 0.02, 0.01 for 90 to 105 cm; 0.10, 0.10, 0.02, 0.02 for 105 to 120 cm. LSD at $P = 0.05$ for comparison of depth within rootstock: 1.3 for MAC.24 (■); 0.9 for OAR 1 (●); 1.0 for M.26EMLA (▲); 0.7 for M.9EMLA (□); 0.6 for M.7EMLA (○) and O.3 (△); 0.5 for M.9 (light diamond) and MAC.9 (dark diamond).

Table 3. Relationship between total root number and root size category having the highest coefficient of determination vs. scion vigor and yield for all rootstocks.

y Parameter	x Parameter	Equation	R^2	P value
		Marlette soil		
Trunk cross-sectional area (cm^2)	Total roots	y = 13.504 + 0.039x	0.39	0.001
	Large roots	y = 18.430 + 1.880x	0.61	0.001
Tree height (m)	Total roots	y = 199.932 + 0.076x	0.29	0.001
	Large roots	y = 2.009 + 0.036x	0.45	0.001
Canopy spread (m)	Total roots	y = 195.213 + 0.064x	0.24	0.001
	Large roots	y = 2.043 + 0.030x	0.37	0.001
		Canfield soil		
Trunk cross-sectional area (cm^2)	Total roots	y = 26.076 + 0.617x	0.36	0.001
	Medium and large roots	y = –43.698 + 7.789x	0.65	0.001
Tree height (m)	Total roots	y = 1.949 + 0.001x	0.28	0.001
	Medium and large roots	y = 1.752 + 0.014x	0.58	0.001
Canopy spread (m)	Total roots	y = 2.702 + 0.001x	0.08	0.090
	Medium and large roots	y = 2.251 + 0.011x	0.42	0.001
1989 Yield (kg)	Total roots	y = 14.199 + 0.036x	0.22	0.005
	Medium and large roots	y = 4.173 + 0.516x	0.54	0.001
10-Year cumulative yield (kg)	Total roots	y = 98.498 + 0.090x	0.23	0.005
	Medium and large roots	y = 80.809 + 1.209x	0.48	0.001

Table 4. Relationship between number of combined medium and large roots vs. scion vigor and yield for M.7 EMLA and relationship between small roots vs. combined medium and large roots for all rootstocks.

y Parameter	x Parameter	Equation	R^2	P value
		Marlette soil		
Small roots	Medium and large roots	y = 212.700 + 13.760x	0.73	0.001
M.7EMLA small roots	M.7EMLA medium and large roots	y = 433.890 + 7.430x	0.94	0.010
		Canfield soil		
M.7EMLA TCA (cm^2)	Medium and large roots	y = 166.620 – 0.691x	0.95	0.010
M.7EMLA tree height (m)	Medium and large roots	y = 8.033 – 0.043x	0.98	0.010
M.7EMLA 1989 Yield (kg)	Medium and large roots	y = 226.110 – 1.461x	0.97	0.010
M.7EMLA 10-Year cumulative yield (kg)	Medium and large roots	y = 486.280 – 2.486x	0.99	0.010
Small roots	Medium and large roots	y = 440.180 + 5.945x	0.49	0.001
M.7EMLA small roots	M.7EMLA medium and large roots	y = 2593.900 – 17.173x	0.73	0.050

large roots vs. TCA, tree height and canopy spread for the Marlette soil are shown in Table 3. All linear regression models between number of roots (total roots and all size categories) vs. TCA, tree height, canopy spread, 1989 yield and 10-year cumulative yield for trees in the Canfield soil were highly significant ($P < 0.01$) except for total and small roots vs. canopy spread. Maximum R^2 values were found for medium or large roots vs. the vigor and yield parameters for trees in the Canfield soil. These two categories were analyzed together as combined medium and large roots and were compared with the vigor and yield components listed above. The R^2s for combined medium and large roots were higher than for medium or large roots alone for trees in the Canfield soil. Regression models for total roots and combined medium and large roots vs. vigor and yield parameters for the Canfield soil are shown in Table 3.

Scion vigor and the intensity and extensiveness of the root system has been shown to be positively correlated for many apple rootstocks (Atkinson, 1980; Avery, 1970; Coker, 1958; Rogers and Vyvyan, 1934). The positive relationship found for TCA, tree height, and canopy spread of the scion vs. number of roots counted demonstrates that tree vigor can be used to give a rough estimate of root system size of these rootstocks with the exception of M.7EMLA for these soils. The higher correlation coefficients with medium and large roots could reflect their longevity, which may indicate a cumulative measure of root system size in the same way that TCA, tree height, and canopy spread reflect a cumulative measure of the above ground portion of the tree, whereas, a substantial proportion of the small roots may die (Smucker, 1984).

Linear regression analysis showed a positive correlation between 1989 yield and cumulative yield vs. the number of total roots counted for the Canfield soil. The R^2s were much higher for 1989 yield and cumulative yield vs. combined medium and large roots in the Canfield soil than for total roots (Table 3). The higher correlation between medium and large roots with yield parameters in the Canfield soil may be related to over-winter carbohydrate storage in these roots as larger roots are more likely to over winter and store larger amounts of carbohydrates than small roots (Kramer and Kozlowski, 1979; Abod and Webster, 1991). Also, the contribution of older roots to water and nutrient uptake during the summer and early fall can be substantial when water demand is highest, when new root growth lowest and there is a high fruit growth rate (Atkinson, 1980; Rom, 1987). No significant correlation was found for yield parameters and root numbers in the Marlette soil. This may be due to a smaller percentage of medium and large roots compared to small roots in the Marlette soil than the Canfield soil (Fernandez et al., 1991).

It was noticed that M.7EMLA displayed a negative slope on most of the regression lines where all rootstocks were included. Therefore, individual rootstocks were subjected to regression analysis for total roots and all size categories vs. growth and yield parameters. All rootstocks were found to have a positive or nonsignificant relationship individually (data not shown) except M.7EMLA. A strong negative relationship was found for M.7EMLA between TCA, tree height, 1989 yield, and 10 year cumulative yield compared with root data for the Canfield soil. Maximum R^2 was found for growth and yield parameters vs. combined number of medium and large roots (Table 4). Negatives slopes also were detected for tree height, canopy spread and 1989 yield vs. combined medium and large roots for the Marlette soil, although the relationships were not significant (data not shown).

As a result of these findings, the relationship between the number of small roots to number of combined medium and large roots was examined for all rootstocks combined and individual rootstocks. For all rootstocks combined, there was a significant positive relationship between the number of small roots vs. combined medium and large roots. The same results were obtained for regression analysis of individual rootstocks except M.7EMLA, which displayed a strong negative correlation in the Canfield soil but a positive correlation for the Marlette soil (Table 4).

The highly significant negative correlations found in the Canfield soil for M.7EMLA between combined medium and large roots vs. TCA, tree height, 1989 yield, cumulative yield and small root number may indicate a strong competition for carbohydrates between the medium and large roots and the rest of the plant. The positive relationship between combined medium and large roots vs. small roots over all rootstocks demonstrates a balanced root system. The strong negative correlation between combined medium and large roots vs. small roots for M.7EMLA in the Canfield soil indicates an unbalanced root system under these soil conditions.

The negative relationship between combined medium and large roots vs. small roots observed for the Canfield soil may explain observations of poor anchorage, leaning, and an asymmetric root system of M.7EMLA under certain situations (Ferree and Carlson, 1987). Medium and large roots accounted for only 8% of the root system for M.7EMLA in the Canfield soil (Fernandez et al., 1991) but with an increase from ≈75 to 105 medium and large roots, there was a decrease from approximately 1150 to 650 small roots, i.e., for each increase of one medium or large root there was a decrease of 17 small roots. This large reduction in the number of small roots with a slight increase in medium and large roots could explain poor anchorage of M.7EMLA under circumstances where more larger roots are produced.

The greatest effect on the total number of roots/dm^2 over all depths was due to rootstock. Rootstocks were similar at both soil types with respect to the total number of roots/dm^2 and small roots/dm^2 over all depths with only three rootstocks exhibiting differences due to soil type. MAC.9 formed more roots/dm^2 than expected when compared to tree vigor in the Canfield soil and had a higher relative ranking than in the Marlette soil. M.9EMLA formed more roots/dm^2 than expected when compared to tree vigor in the Marlette soil and had a higher relative ranking than in the Canfield soil. M.7EMLA formed fewer roots/dm^2 than expected when compared to tree vigor in the Marlette soil and a lower relative ranking than in the Canfield soil.

The overall size of the root system appeared to be controlled by the genotype while the root distribution pattern was affected by the soil environment. An even distribution of roots or moderate decrease in the number of roots/dm^2 with greater depths was observed for trees in the lighter fine sandy loam (Marlette) but a restriction of most roots above the fragipan was seen for trees in the heavier silt loam (Canfield). The soil volume available to the root systems of trees in this study was greatly reduced in the Canfield soil by the fragipan. Additionally, up to twice as many roots/dm^2 were present in the zone above the fragipan in the Canfield soil than at the same depths for the Marlette soil. Plants with large root systems restricted to small soil volumes, such as was found for MAC.24 in the Canfield soil, are likely to respond differently to environmental conditions or imposed treatments compared to the same plants with unrestricted soil volumes. The combination of a high root density in a shallow soil volume could alter plant response to soil stresses such as flooding or drought stress by more rapid depletion of soil water and gases. Positive relationships were found for vigor and yield parameters compared with number of roots for all rootstocks except M.7EMLA where a possible competitive effect was found between vigor, yield, and small roots vs. combined medium and large roots. Based on relative ranking of rooting intensity for the two soil types M.9EMLA, MAC.9, and M.7EMLA were affected by soil type. It is important to consider the ability of plants to alter root distribution patterns without apparent reductions in the overall size of the root system in response to changes in the soil environment as found in this study when selecting rootstocks and management systems both for orchardists and researchers.

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